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Simon Elias Bibri

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Doctoral theses at NTNU, 2021:171

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of
Philosophiae Doctor
Faculty of Information Technology and Electrical
Engineering
Department of Computer Science

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A Strategic Planning Process of Transformative Change towards Sustainability

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Abstract

Sustainable cities have been the leading global paradigm of urbanism and the most preferred response to the challenges of sustainable development. Significant advances have been achieved in knowledge and a multitude of exemplary practical initiatives have been realized, thereby raising the profile of sustainable cities worldwide over the last four decades or so. The change is still inspiring and the endeavor continues to induce scholars, practitioners, and policymakers to enhance the existing models of sustainable cities, or to propose integrated models in response to new global trends and paradigm shifts in science and technology. Besides, sustainable cities epitomize complex systems par excellence, and as such, they are characterized by wicked problems. The problematicity surrounding sustainable cities lies in their development planning approaches and operational management mechanisms, as well as the fragmentary design strategies and environmental technology solutions pertaining to compact cities and eco-cities, respectively. This has a clear bearing on the performance of sustainable cities with respect to their contribution to the three goals of sustainability. This situation is compounded by the escalating trend of urbanisation and its negative consequences. Most of the problems, issues, and challenges related to sustainable cities largely relate to how these human settlements should be monitored, understood, analyzed, planned, designed, and managed in order to improve and advance sustainability. The underlying argument is that more innovative solutions and sophisticated methods are needed to tackle the kind of complexities and wicked problems inherently embodied in sustainable cities. This in turn brings us to the issue of sustainable cities and smart cities being extremely fragmented as landscapes and weakly connected as approaches, both at the technical and policy levels. Therefore, sustainable cities need to embrace and leverage what smart cities have to offer so that they can optimize, enhance, and maintain their performance and achieve the desired outcomes of sustainability. Especially, it has become increasingly feasible to attain important improvements and advancements of sustainability by integrating these two models of urbanism thanks to the proven role and untapped potential of data-driven technologies as an advanced form of ICT.

The aim of this PhD study is to analyze, investigate, and develop a novel model for data-driven smart sustainable cities of the future. Using a methodological framework combining normative backcasting and descriptive case study as qualitative approaches, the study is performed through the assessment of the current situation, the analysis of major societal trends, the generation of a vision of a desired future, the investigation and understanding of the prevailing models of sustainable urbanism and the emerging models of smart urbanism in their real-world settings, and the development of the strategic planning process of transformative change towards sustainability. The contributions of the PhD study are as follows:

C1: Analysis and evaluation of the state of the art in smart sustainable cities
C2: Analysis and evaluation of the state of the art in smart cities of the future
C3: Assessment of the current situation and trend analysis
C4: Construction of the future vision
C5: Illumination of the urbanism paradigms underpinning the strategic planning process of backcasting
C6: Development of an applied theoretical framework for strategic sustainable urban development planning
C7: Development of a novel model for data-driven smart sustainable cities of the future

The proposed model serves as a strategic sustainable urban development framework for facilitating progress towards achieving the long-term goals of sustainability for those cities that are badging or regenerating themselves as sustainable, or manifestly planning to be or become smart sustainable in the era of big data. It is, to the best of our knowledge, the first of its kind and thus has not been produced elsewhere.

Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) in partial fulfilment of the requirements for the degree of *philosophiae doctor* (*PhD*).

The work has been performed at the Department of Computer Science, NTNU, Trondheim, with Professor John Krogstie as the main supervisor and Professor Tor Medalen, Professor Yngve Karl Frøyen, and Professor Monica Divitini as co-supervisors.

The work presented in this thesis is conducted in the context of the project of Sustainable Urban Planning and ICT as an enabling technology.

Acknowledgements

I would like to express my deepest gratitude to Professor John Krogstie for giving me the opportunity to pursue this PhD study and making it possible, coordinating the research project with the Department of Architecture and Planning, allowing me to choose the topic that I am passionate about, providing constant support, and for believing in my intellectual abilities. It has been a delight having him as my main supervisor and thus an invaluable reference of guidance and advice throughout this research endeavor.

I owe a great deal of gratitude to Professor Mattias Kärrholm for his hospitality and the rewarding six-month experience as a visiting researcher in the Department of the Built Environment and Architecture at Lund University, as well as for the fruitful discussions on the two cases I was investigating in Sweden in 2019. His good nature and humbleness made learning from, and sharing knowledge with, him such a delight. A special thanks goes to all the interviewees who participated in my case study research. I also acknowledge all the researchers with whom I had the chance to exchange ideas during my research stay in Sweden.

I would like to take this opportunity to express my sincere appreciation to the administrative and technical staff at the Department of Computer Science for the immense support they delivered throughout this research project. I owe special thanks to my colleagues at IDI for their support. I extremely enjoyed working with everyone at IDI. I would like to extend my special thanks to Senior Researcher Dirk Ahlers and Associate Professor Patrick Mikalef for the fruitful discussions we had.

Last but not least, I would like to express my deepest gratitude to my sister, Amina, for her moral support and for making it possible for me to continue my lifelong pursuit of knowledge. You have made this piece of work and this intellectual journey possible in more ways than one.

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1. Introduction

Urbanization is one of the greatest challenges facing cities of the future. In recent decades, urban growth has been dramatic. For the first time in history, more than half the world's population lives in urban areas. This is estimated to rise to 70% by 2050, with an annual population growth of 50-60 million inhabitants. As an irreversible global trend, urbanization involves a multitude of environmental, social, economic, and spatial conditions, which pose unprecedented challenges to politicians, policy makers, planners, and other practitioners. Indeed, the intractable issues engendered and special conundrums posed by urban growth exacerbate the wicked problems characterizing cities as complex systems.

Nevertheless, cities are a mark of human civilisation and play a central role in the pursuit of new paradigms of thinking to bring about major transformations to the way people live. Sustainability has, over the last four decades, been one of the most influential paradigms of thinking within urbanism. Modern cities holding unparalleled potential to address and overcome the challenges of sustainable development largely depends on how they can be planned, designed, and managed in response to global trends, scientific discoveries, and technological advances. This is clearly reflected in the Sustainable Development Goal (SDG) 11 of the United Nations' 2030 Agenda—Sustainable Cities and Communities (United Nations 2015a). Appropriately redesigning and restructuring urban places as sustainable cities and adopting innovative solutions to make urban living more sustainable is a continuous endeavor towards achieving the long-term goals of sustainability. The subject of "sustainable cities" remains endlessly enticing given that there are numerous actors involved in the academic and practical aspects of the endeavor, including planners and architects, built and natural environment specialists, and social scientists, as well as computer scientists, data scientists, and urban scientists. All these actors are undertaking research and developing strategies and approaches to tackle the challenging elements of sustainable urban development. In addition to this work is the effort of decision-makers in terms of devising and applying political mechanisms, policy makers in terms of formulating and implementing regulatory frameworks, and institutional actors in terms of facilitating the coordination between a range of actors and networks, all to promote and spur innovation and monitor and maintain progress towards sustainable cities.

Sustainable cities have, since the late 1980s, been the leading global paradigm of urbanism thanks to the models of sustainable urban form proposed as new frameworks for redesigning and restructuring urban places in ways that respond to the objectives of sustainable development, notably compact cities and eco-cities. These are the central paradigms of sustainable urbanism and thus promoted by global and local policies as the preferred response to the challenges of sustainable development. Compact cities and eco-cities continue to strive towards reaching the optimal level of sustainability by enabling the built environment to function in ways that further reduce material use, lower energy consumption, mitigate pollution, and minimize waste, as well as improve social equity and human well–being.

Significant advances have been achieved in some areas of knowledge and a multitude of exemplary practical initiatives have been realized, thereby raising the profile of sustainability and sustainable cities worldwide. The change is still inspiring and the endeavor continues to induce scholars, practitioners, and policymakers alike to enhance the existing models of sustainable urban form, or to propose integrated models in response to the global trends and scientific and technological shifts at play today, notably the spread of urbanization and the rise of the IoT and big data technologies. Transformative processes within sustainable cities have been on focus for some time now. The motivation for achieving the United Nations' SDG 11 has increased the need to understand, plan, and manage sustainable cities in new and innovative ways (United Nations 2015a). In this respect, the United Nations's 2030 Agenda regards advanced ICT as a means to promote socio–economic development and protect the environment, increase resource efficiency, achieve human progress and knowledge in societies, upgrade legacy infrastructure, and retrofit industries based on sustainable design principles (United Nations 2015b). This relates to the multifaceted potential of smart cities, which has been under study with respect to the role of big data technologies and their novel applications in strategic sustainable development in relation to 2030 Agenda (United Nations 2015c). The abundance of urban data, coupled with their analytical power, opens up for new opportunities for innovation in sustainable cities. This in turn means tackling the problems and challenges facing sustainable cities in their endeavor to make actual progress towards achieving the long-term vision of sustainability.

Science-based technology is well aligned with the project of envisioning and enacting visions of sustainable futures. Advances in science and technology inevitably bring with them wide–ranging common visions on how cities will evolve in the future, as well as the opportunities and risks that future will bring. At the beginning of a new decade, we have the opportunity to look forward and consider what we can achieve in the era of big data in the coming years. Sustainable cities look further into the future when forming strategies and pathways, and the movement towards a long–term vision arises from the three major mega trends that are shaping our society at a growing pace, namely sustainability, urbanization, and ICT. In recognizing a link between these trends, sustainable cities across the globe need to adopt ambitious goals that extend far into the future and develop new strategies and pathways to achieve such goals.

1.1. Problem Discussion

Sustainable urbanism is seen today as one of the keys towards unlocking the quest for a sustainable society. Compact cities and eco-cities are the central paradigms of sustainable urbanism and the most advocated models of sustainable cities. Compact cities emphasize the economic dimension of sustainability, whereas eco-cities emphasize the environmental dimension of sustainability. As to the social dimension of sustainability, it is of less focus in eco-cities than in compact cities. However, emphasizing one of the dimensions of sustainability remains a shortcoming (failure to meet certain standards in plans) and deficiency (lacking some necessary elements) in the urban context. Indeed, urban sustainability is a holistic approach to thinking, meaning that all the three dimensions of sustainability should be equally important. Therefore, it is of high relevance and importance to integrate the models of compact cities and eco-cities so as to consolidate and harness their design strategies and sustainable technologies to deliver the best outcomes of sustainability within the framework of sustainable cities.

Furthermore, the conscious push for sustainable cities to become smarter and thus more sustainable in the era of big data is due to the problematicity surrounding their development planning approaches and operational management mechanisms, as well as the fragmentation of their designs and technologies related to the compact city and eco-city models of sustainable urban form. This has a clear bearing on their performance with respect to the contribution to and balancing of the goals of sustainability. This situation is compounded by the negative consequences of urbanization. To address these challenges, advanced forms of ICT are needed. New and emerging technologies offer great potentials and opportunities for innovation that can produce a high quality of life and fuel sustainable economic development together with a wise management of natural resources. They are also of crucial importance to the understanding of sustainable cities as complex systems—dynamically changing environments and self-organizing social networks embedded in space and enabled by infrastructures, activities, and services. Therefore, it is necessary to develop and apply more sophisticated approaches and innovative solutions to the development planning and operational management of sustainable cities. In response to this, sustainable cities are increasingly adopting data-driven technologies so as to tackle the complexities they inherently embody and, thus, to optimize, enhance, and maintain their performance with respect to sustainability—under what has been termed “data-driven smart sustainable cities.”

The issues, problems, and challenges related to sustainable cities largely pertain to the question of how they should be monitored, understood, analyzed, planned, designed, and managed to improve and advance their contribution to and balancing of the goals of sustainability. This brings us to the question related to the weak connection between sustainable cities and smart cities as approaches as well as their extreme fragmentation as landscapes, both at the technical and policy levels. The real challenge for the future lies in moving genuinely past the assumption that there are only two contrasting, mutually exclusive realities or choices. An 'either/or' approach will hamper progress towards urban sustainability, as the huge challenges facing sustainable cities within many of their administration spheres require an integrated model of urbanism. Therefore, sustainable cities need to embrace and leverage what smart cities have to offer in terms of advanced solutions in order to achieve the desired outcomes of sustainability. Especially, it has become feasible to attain important improvements of sustainability by integrating these two prevailing models of urbanism thanks to the proven role, substantive impact, and untapped potential of data-driven technology solutions.

1.2. Research Context

The PhD research has been conducted at the Department of Computer Science at NTNU. The research work is part of the NTNU's strategic research area on Sustainable Development. The initiative on Sustainable Societal Development was at the start of the work divided into four main focus areas, namely:

1. Institutional framework conditions, the conditions necessary for sustainable policies and practices
2. **Sustainable urban development**
3. Biodiversity and ecosystem services, knowledge about how human activities affect biodiversity and ecosystem functions
4. Analysis of environment and sustainability, advanced modeling and analysis of sustainability at the society, business and production levels

Four cross-cutting initiatives transverse the main focus areas:

1. Ethical perspectives related to sustainability
2. **ICT as an enabling technology**
3. Land use and the sustainable use of natural resources
4. Sustainable design and business models,

The PhD research is concerned with the focus area of sustainable urban development (sustainable cities) and the cross-cutting initiative of ICT as an enabling technology (data-driven technologies). In short, advanced ICT for urban sustainability.

As stated in the initiative with regard to sustainable urban development, there is a need for theoretical and empirical research addressing the interaction between urban development strategies, technology, architecture and urban design, everyday life, land use, infrastructure and transport. Issues such as inequality, production, and consumption in the urban communities of the future are key to the development of sustainable cities. As stated in the initiative with respect to ICT as an enabling technology and a cross-cutting research challenge, ICT systems are everywhere in society, and modern societies depend on a large number of well-functioning ICT systems, including the infrastructure that links the systems together. Sustainable solutions include ICT as an enabling technology.

With the above in mind, the main focus of this research is on how to improve, advance, and maintain the contribution of sustainable cities to the goals of sustainability on the basis of the data-driven technologies and solutions offered by smart cities of the future. To accomplish this, we imagined and articulated a vision for a desired future while grounding it in realism, and then we determined the actions and measures to be undertaken to reach that specified future. The main goal of this research is to build a novel model of urbanism integrating the design strategies and environmental technology solutions of sustainable cities with the applied data-driven technology solutions of smart cities for sustainability. The results from this research work have been published in internationally peer-reviewed journals, conferences, and book series.

1.3. Research Aim and Objectives

The aim of the PhD study is to analyze, investigate, and develop a novel model for data-driven smart sustainable cities of the future using backcasting as a strategic planning approach. This model integrates the prevailing paradigms of sustainable urbanism and the emerging paradigms of smart urbanism, namely compact cities, eco-cities, data–driven smart cities, and environmentally data-driven smart sustainable cities in terms of their dimensions, strategies, and solutions. As such, it is grounded in case study research, which was carried out on a total of six of the ecologically and technologically leading cities in Europe.

The objectives of the PhD study, the specific steps to be taken to achieve the research aim, are:

- Conduct trend analysis and identity the main expected developments related to the new model of urbanism.
- Clarify the current situation of sustainable cities in relation to smart cities.
- Generate a vision for a sustainable future based on the outcome of the trend analysis and the current situation.
- Specify the objectives and targets for achieving the overall goal of the future vision.
- Examine the compact city and the eco-city as the central paradigms of sustainable urbanism and the extent to which these contribute to the goals of sustainability.
- Integrate the theoretically informed, practically successful, and widely adopted design strategies of the compact city and design and environmental technology solutions of the eco-city, predicated on the assumption that the former has a form and the latter is formless.
- Examine the emerging data-driven smart city in terms of what it takes to integrate modern technology and implement applied technology solutions in city development planning and city operational management.
- Examine the potential and role of emerging data-driven solutions in improving and advancing environmental sustainability within the framework of environmentally data-driven smart sustainable cities.
- Distill and integrate all the components underlying the examined models of urbanism into a framework for strategic sustainable urban development planning.
- Develop pathways (actions and measures) for executing the set of strategies identified in order to achieve the specified objectives and targets related to sustainability and thus the overall goal of the future vision.

1.4. Research Questions

The topic of the PhD study revolves around the planning of data-driven smart sustainable cities of the future based on the strategic process of backcasting as a framework for sustainable development. Based on the aim, objectives, and methodological framework, the following main research question and subquestions were defined to guide the research project.

Main research question:

The scope of the main research question is informed by the research aim. The main research question is formulated as follows:

How to improve, advance, and maintain the contribution of sustainable cities to the goals of sustainability on the basis of the data-driven technologies and solutions offered by smart cities of the future?

The research subquestions are formulated as follows:

RQ1: What are the key problems, issues, and challenges related to sustainable cities, and how can they be addressed and overcome based on the new technologies offered by smart cities of the future?

RQ2: What is the status of the current model of urbanism and what are the dominating trends and expected developments related to the future model of urbanism?

RQ3: How does the future vision look like and how is it different from the current model of urbanism?

RQ4: How are the four models of urbanism underlying the future vision practiced and justified with respect to sustainability, and in what ways can they complement each other in that respect?

RQ5: What are the dimensions, strategics, and solutions of the future model of urbanism?

RQ6: How can these components be integrated into a framework for strategic sustainable urban development planning?

RQ7: What are the benefits, potentials, and opportunities of the future model of urbanism?

RQ8: What kind of transformations are necessary for attaining the future vision, and what are the key strategies and pathways needed to bring about these transformations?

The relationship between the research questions is essentially sequential as all backcasting-oriented futures studies are depicted stepwise. Accordingly, the research questions are associated with the analysis, envisioning, investigation, and development of a novel model for data-driven smart sustainable cities of the future. Answering RQ1 is a preparatory task to get an understanding of the research problem and its potential solution. RQ2 draws on RQ1. The problem and solution understanding and the external factors identified in RQ1 together act as a basis for the construction of the future vision in RQ2. RQ2 is further underpinned by the outcome of the empirical investigation carried out in RQ3 in relation to the underlying components of the future vision. These components pertain to the prevailing paradigms of sustainable urbanism and the emerging paradigms of smart urbanism in terms of their dimensions, strategies, and solutions addressed in RQ4. These are integrated into a framework for strategic sustainable urban development planning in RQ5. RQ6 addresses the combined and added value of turning this framework into a new model of urbanism. RQ7 develops and elaborates in more detail on the new model of urbanism.

1.5. Research Publications

The methodological framework applied in the PhD study integrates normative backcasting and descriptive case study (see Chapter 3 for further discussion) as qualitative approaches. It was used to explore the topic of data-driven smart sustainable cities of the future, a process that involves six steps (Table 1.1) resulting in a number of study areas and related publications. This methodological framework is described in more detail in Chapter 3. Worth noting is that the answer to the guiding questions for each of these steps may involve one, two, or more papers, and one paper may in turn answer the guiding questions for one or two steps.

Steps	Research Activities
Step 1	Research design and problem formulation
Step 2	Trend analysis and current situation
Step 3	Future vision construction
Step 4	Case study research
Step 5	Framework development
Step 6	Backcasting analysis

Table 1.1 Six step and related research activities

This subsection presents an overview of the research publications pertaining to the PhD study from P1 to P13. These papers are grouped according to Table 1, in addition to the comprehensive literature studies underpinning the field of data-driven smart sustainable urbanism from a general perspective. Each paper is presented based on the published title, authors, publication details, and abstract, followed by a brief description in relevance to the thesis.

1.5.1. Comprehensive Literature Studies

P1: Bibri, Simon Elias and Krogstie, John: **"Smart Sustainable Cities of the Future: An Extensive Interdisciplinary Literature Review"**. Sustainable Cities and Society 2017; Volume (31) pp.183-212

Relevance to the Thesis: P1 gives insights into the state-of-the-art research in sustainable cities and smart cities as the two main research areas of the PhD study, as well as their integration. It provides a foundation for the PhD study in terms of what is already known, produces a rationale for the PhD study as to its contribution of something new to the body of knowledge, helps understand where excess research exists and what kind of questions are left unanswered, and accordingly substantiates the presence of the research problem in regard to what should be known. In particular, this paper states the research problems and their potential solutions, showing how the knowledge gaps can be filled within the field of sustainable cities. It also justifies the further investigation of sustainable cities in terms of compact cities and eco-cities to find out whether any progress has been recently made towards urban sustainability (P6 and P7). This is intended to inform the development of the new model of urbanism proposed by this review paper. This paper contributes to answering RQ1 and produces C1.

P2: Bibri, Simon Elias: **"On the Sustainability of Smart and Smarter Cities and Related Big Data Applications: An Interdisciplinary and Transdisciplinary Review and Synthesis"**. Journal of Big Data 2019; Volume 6.(25) pp. 1-64

Relevance to the Thesis: P2 expands on P1 with respect to the second main research area of the PhD study. In so doing, it presents the current status of the body of knowledge in the field of smart cities of the future from a sustainability perspective. This helps to understand the feasible solutions for the problems, issues, and challenges related to sustainable cities (P1) by highlighting the potentials and opportunities of data-driven technologies for advancing sustainability within smart cities of the future. The identified data-driven technology solutions are intended to be applied in the operational management and development planning of sustainable cities in order to improve and advance their contribution to the goals of sustainability. In addition, this paper presents the relevant research issues associated with smart cities of the future and the challenges they are facing in relation to the use and application of data-driven technologies. In relation to the former, this paper justifies the further investigation of smart cities to find out the extent to which they incorporate the goals of sustainability in their development strategics, as well as which of these goals they tend to prioritize. Concerning the latter, it is implied that sustainable cities are also concerned with and need to address and overcome the same challenges in order to successfully implement data-driven technology solutions so as to optimize, enhance, and maintain their performance with respect to their contribution to sustainability. This paper contributes to addressing RQ1 and leads to C2.

1.5.2. Trend Analysis and Current Situation

P3: Bibri, Simon Elias and Krogstie, John: **"A Scholarly Backcasting Approach to a Novel model for Smart Sustainable Cities of the Future: Strategic Problem Orientation "**. Journal of Futures Studies 2019; Volume 6.(3) pp. 1-27

Relevance to the Thesis: P3 details the strategic problem orientation of the futures study in terms of the current situation and the dominating trends and expected developments related to the future model of urbanism to be investigated and developed. As regards the current situation, it focuses on the problems, issues, and challenges pertaining to sustainable cities addressed by the PhD study, unlike P1 and P2 which provide a state-of-the-art review from a broader perspective. Additionally, it outlines the long-term objectives and targets related to sustainability. These are to be refined based on the outcomes of the four case studies to be conducted. Furthermore, it provides the evaluation for grounding the future vision to be constructed in realism, thereby underpinning the normative side of backcasting. This paper addresses RQ1 and results in C3. It represents the Steps 1 and 2 of the futures study.

1.5.3. Future Vision Construction

P4: Bibri, Simon Elias and Krogstie, John: **"Generating a Vision for Smart Sustainable Cities of the Future: A Scholarly Backcasting Approach"**, European Journal of Futures Research 2019; Volume 7.(5) pp. 1-20

Relevance to the Thesis: Reaching the goals of urban sustainability is an unlikely outcome of any effort deployed for advancing sustainable cities without first defining a future place where to land. In this light, P4 generates a vision for a sustainable future to be attained based on the outcome of P3, and addresses several related issues in relevance to Step 3 of the futures study. At the core of this vision is the integration of sustainable cities and smart cities on the basis of big data technologies—in short, data-driven smart sustainable cities of the future. This paper highlights the prevailing tendency to direct the recent advances in ICT towards addressing and overcoming the mounting challenges of sustainability in the light of the escalating trend of urbanization. Overall, it initiates the backcasting process by envisioning and analyzing the state of the future and thus clarifying the new model of urbanism to be investigated (P5, P6, P7, P8, and P9). This paper answers RQ2 and produces C4. It represents the Step 3 of the futures study.

1.5.4. Case Study Research

P5: Bibri, Simon Elias: **"A Methodological Framework for Futures Studies: Integrating Normative Backcasting Approaches and Descriptive Case Study Design for Strategic Data-Driven Smart Sustainable City Planning"**. Energy Informatics 2020; Volume 3.(31) pp. 1-42

Relevance to the Thesis: P5 focuses on the methodological framework applied in the futures study, which combines normative backcasting and descriptive case study as qualitative approaches. The backcasting approach was employed to achieve the overall aim of the futures study. The case study approach, which concerns the empirical phase of the futures study, was adopted to examine and compare two of a total of six cases in each of the four case studies conducted on compact cities, eco-cities, data–driven smart cities, and environmentally data-driven smart sustainable cities. The methodological framework explores the topic of data-driven smart sustainable cities of the future, a novel model of urbanism that integrates these four models of urbanism. This paper contributes partially to answering RQ3 and partially to producing C5. This paper constitutes part of the Step 4 of the futures study.

P6: Bibri, Simon Elias, Krogstie, John and Kärrholm, Mattias: **"Compact City Planning and Development: Emerging Practices and Strategies for Achieving the Goals of Sustainability"**. Developments in the built environment 2020; Volume 4 pp. 1-20

P7: Bibri, Simon Elias and Krogstie, John: **"Smart Eco–City Strategies and Solutions: The Cases of Royal Seaport, Stockholm, and Western Harbor, Malmö, Sweden"**. Urban Science 2020; Volume 4.(1) pp. 1-42.

P8: Bibri, Simon Elias and Krogstie, John: **"The emerging Data–driven Smart City and its Innovative Applied Solutions for Sustainability: The cases of London and Barcelona"**. Journal of Energy Informatics 2020; Volume (3).5 pp. 1-42

P9: Bibri, Simon Elias and Krogstie, John: **"Environmentally Data-driven Smart Sustainable Cities: Applied innovative Solutions for Energy Efficiency, Pollution Reduction, and Urban Metabolism".** Energy Informatics 2020; Volume (3).29 pp. 1-59

Relevance to the Thesis: P6, P7, P8, and P9 illuminate the urban phenomena of compact urbanism, ecological urbanism, data–driven smart urbanism, and environmentally data-driven smart sustainable urbanism. The outcome of this work has a threefold purpose. Firstly, it provides the foundational elements of the framework for strategic sustainable urban development planning that is to be developed by means of P10. Secondly, it refines the vision of the future (P10) and thus the broadly defined objectives and targets it is translated to (P11) in the light of the new insights gained from the case study research conducted. Thirdly, it underpins and informs the development of the novel model for data-driven smart sustainable cities of the future (P11, P11, and P13). The four papers, combined, contribute to answering RQ4 and generate C5. They represent together with P5 Step 4 of the futures study.

1.5.5. Framework Development

P10: Bibri Simon Elias and Krogstie John: **"Data-Driven Smart Sustainable Cities of the Future: A Novel Model of Urbanism and its Core Dimensions, Strategies, and Solutions"**. Journal of future Studies 2020; Volume 25(2). pp. 77–94

Relevance to the Thesis: P10 presents the results of the four case studies in terms of the dimensions, strategies, and solutions of the prevailing models of sustainable urbanism and the emerging models of smart urbanism. This in turn allows to identify the underlying components of the future model of urbanism and then to integrate them into the framework for strategic sustainable urban development planning proposed in P1. The intent of this applied theoretical framework (derived based on the outcomes of P6, P7, P8, and P9) is to guide the development of the novel model for data-driven smart sustainable cities of the future (P11, P12, and P13). The first part of P13 identifies the key benefits of sustainable cities and the potentials and opportunities of smart cities for boosting these benefits with respect to the three dimensions of sustainability and their balanced integration. In this respect, it highlights the added value of the future vision and thus justifies the adoption of the future model of urbanism. P10 answers RQ5 and RQ6 and the first part of P13 answers RQ6. P10 and the first part of P13 result in C6. They represent the Step 5 of the futures study.

1.5.6. Backcasting Analysis

P11: Bibri, Simon Elias and Krogstie John: **"A Novel Model for Data-Driven Smart Sustainable Cities of the Future: A Strategic Roadmap to Transformational Change in the Era of Big Data"** . Future Cities and Environment 2021; Volume 7(1).3 pp. 1–25

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P12: Bibri, Simon Elias: **“Data-driven Environmental Solutions for Smart Sustainable Cities: Strategies and Pathways for Energy Efficiency and Pollution Reduction”**. Euro-Mediterranean Journal of Environmental Integration; Volume (5).66 pp. 1-6

P13: Bibri, Simon Elias: **“A Novel Model for Driven Smart Sustainable Cities of the Future: The Institutional Transformations Required for Balancing and Advancing the Three Goals of Sustainability”** . Journal of Energy Informatics 2021, Volume (4).4 pp. 1-37

Relevance to the Thesis: P 11, P12, and the second part of P13 present the novel model for data-driven smart sustainable cities of the future. This takes the form of a full strategic planning process of transformative change towards sustainability, meaning the broadly defined objectives and targets, the future vision, and the strategies and pathways needed to attain it. P 11 is the main contribution to building the novel model for data-driven smart sustainable cities of the future with respect to how to bring about the necessary transformations. P12 and the second part of P13 are complementary to this contribution. P12 is concerned with the smart energy and smart environment transitions related to the essential urban infrastructure. P13 is concerned with the institutional changes necessary for supporting the balancing of the goals of sustainability and for enabling the introduction of data-driven technology and the adoption of applied data-driven solutions in city operational management and development planning. P11, P12, and the second part of P13 provide the actions that meed to be taken and the measures that need to be implemented in order to attain the vision of the future. Accordingly, they represent the analytical side of backcasting, that is, the possible ways of linking the long-term goals of sustainability that lie far ahead in the future to a set of decisive steps that are to be performed now and designed to achieve the preferred future. P 11, P12 and the second part of P13 answer RQ8 and generate C7. They represent the step 6 of the futures study.

The research work has also resulted in a number of publications, including journal articles, conferences, and books. The most relevant among them to the thesis are listed in Appendix B: Secondary Papers.

1.6. Research Contributions

This research has resulted in seven contributions. Each of which is briefly presented below based on the published title, authors, and publication details, thereby providing a kind of mapping between the seven contributions and the research publications. Chapter 4 provides a detailed description of these contributions.

C1: Analysis and evaluation of the state-of-the-art in the fields of sustainable cities and smart cities:

P1: Bibri, Simon Elias and Krogstie, John: “Smart Sustainable Cities of the Future: An Extensive Interdisciplinary Literature Review”. Sustainable Cities and Society 2017; Volume (31) pp.183-212

C2 Analysis and evaluation of the state-of-the-art in the field of smart cities of the future

P2: Bibri, Simon Elias: “On the Sustainability of Smart and Smarter Cities and Related Big Data Applications: An Interdisciplinary and Transdisciplinary Review and Synthesis”. Journal of Big Data 2019; Volume 6.(25) pp. 1-64

C3: Assessment of the current situation and trend analysis

P3: Bibri, Simon Elias and Krogstie, John: “A Scholarly Backcasting Approach to a Novel model for Smart Sustainable Cities of the Future: Strategic Problem Orientation”. Journal of Futures Studies 2019; Volume 6.(3) s. 1-27

C4: Construction of the future vision

P4: Bibri, Simon Elias and Krogstie, John: "Generating a Vision for Smart Sustainable Cities of the Future: A Scholarly Backcasting Approach", European Journal of Futures Research; Volume 7.(5) pp. 1-20

The first part of P13: Bibri, Simon Elias: "A Novel Model for Driven Smart Sustainable Cities of the Future: The Institutional Transformations Required for Balancing and Advancing the Three Goals of Sustainability" . Journal of Energy Informatics; Volume 4.(4) pp. 1-37

C5 Illumination of the urbanism paradigms underpinning the strategic planning process of backcasting

P5: Bibri, Simon Elias: "A Methodological Framework for Futures Studies: Integrating Normative Backcasting Approaches and Descriptive Case Study Design for Strategic Data-Driven Smart Sustainable City Planning". Energy Informatics 2020; Volume 3.(31) pp. 1-42

P6: Bibri, Simon Elias, Krogstie, John and Kärrholm, Mattias: "Compact City Planning and Development: Emerging Practices and Strategies for Achieving the Goals of Sustainability". Developments in the built environment 2020; Volume 4 pp. 1-20

P7: Bibri, Simon Elias and Krogstie, John: "Smart Eco–City Strategies and Solutions: The Cases of Royal Seaport, Stockholm, and Western Harbor, Malmö, Sweden". Urban Science 2020; Volume 4.(1) pp. 1-42

P8: Bibri, Simon Elias and Krogstie, John: "The emerging Data–driven Smart City and its Innovative Applied Solutions for Sustainability: The cases of London and Barcelona". Journal of Energy Informatics 2020; Volume (3).5 pp. 1-42

P9: Bibri, Simon Elias and Krogstie, John: "Environmentally Data-driven Smart Sustainable Cities: Applied innovative Solutions for Energy Efficiency, Pollution Reduction, and Urban Metabolism" Energy Informatics 2020; Volume (3).29 pp. 1-59

C6 Development of an applied theoretical framework for strategic sustainable urban development planning

P10: Bibri Simon Elias and Krogstie John: "Data-Driven Smart Sustainable Cities of the Future: A Novel Model of Urbanism and its Core Dimensions, Strategies, and Solutions". Journal of Future Studies; Volume 25(2). pp. 77–94

P13: Bibri, Simon Elias: "A Novel Model for Driven Smart Sustainable Cities of the Future: The Institutional Transformations Required for Balancing and Advancing The Three Goals of Sustainability" . Journal of Energy Informatics; Volume (4).4 s. 1-37

C7 Development of a novel model for data-driven smart sustainable cities of the future

P11: Bibri, Simon Elias and Krogstie John: "A Novel Model for Data-Driven Smart Sustainable Cities of the Future: A Strategic Roadmap to Transformational Change in the Era of Big Data". Future Cities and Environment; Volume 7(1).3 pp. 1–25

P12: Bibri, Simon Elias: "Data-driven Environmental Solutions for Smart Sustainable Cities: Strategies and Pathways for Energy Efficiency and Pollution Reduction". Euro-Mediterranean Journal of Environmental Integration; Volume (5).66 pp. 1-6

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The second part of P13: Bibri, Simon Elias: “A Novel Model for Driven Smart Sustainable Cities of the Future: The Institutional Transformations Required for Balancing and Advancing the three goals of Sustainability”. Journal of Energy Informatics;Volume (4).4 pp. 1-37

Research Questions	Research publications	Research contributions
RQ1	P1, P2	C1, C2
RQ2	P3	C3
RQ3	P4	C4
RQ4	P5, P6, P7, P8, P9	C5
RQ5	P10	C6
RQ6	P10	C6
RQ7	Part 1 of P13	C6
RQ8	P11, P12, Part 2 of P13	C7

Table 1.2 An overview of research questions in relation to research publications and contributions

1.7. Thesis Structure

The remainder of this thesis is structured as follows:

Chapter 2: State of the Art Review

This chapter provides a state-of-the-art review of the main research areas of the PhD study, and concludes with a research problem statement.

Chapter 3: Research Methodology

This chapter provides an introduction to the methodological background, and describes the research approaches and processes adopted.

Chapter 4: Research Contributions

This chapter presents an overview of the contributions of research work.

Chapter 5: Results

This chapter describes the research results obtained.

Chapter 6: Discussion of Results

This chapter discusses the results in terms of previous studies, the research questions, and the contributions.

Chapter 7: Conclusion and Future Work

This chapter concludes the thesis and provides avenues for future work in relevance to the backcasting study.

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Appendices

Appendix A lists and contains the research publications (P1-P13) that were selected to be included as part of the thesis. Appendix B lists the research publications that contributed to the PhD study but are not included as part of the thesis.

2. A State-of-the-Art Review

The state-of-the-art research presented in this chapter is concerned with the emerging field of data-driven smart sustainable cities. The idea of data-driven smart sustainable cities is still in its infancy. And therefore, a large part of the problems in the field are still not addressed, with many diverse critical aspects being fleshed out as part of the ongoing research endeavors. There are also many problems that have not been addressed well or appropriately by any of the existing research within the field of sustainable cities in relation to their contribution to and balancing of the goals of sustainability, as well how they can be merged with smart cities as landscapes and connected as approaches so as to improve and advance sustainability. The main focus of this research work is on identifying what is missing in the literature on the relationship between sustainable cities and smart cities within the framework of data-driven smart sustainable cities. This field is a fertile area of interdisciplinary research involving numerous intriguing and multifaceted questions awaiting scholars and practitioners from across many city-related disciplines.

2.1 Conceptual Definitions

2.1.1. Sustainable Cities

Despite the fact that the discourse of sustainable cities is now mature and powerful, precise conceptualisations are still rare and often contested. Notwithstanding the universal recognition of sustainable cities being a desirable vision or goal of policy, there is less certainty about what this might mean in practice (Williams 2010). Sustainable cities are so complex and intangible that the notion of what the concept means is constructed in a variety of ways within different city-related disciplines (e.g., engineering, social science, and computing). Consequently, there are multiple views on what a sustainable city should be or look like and thus various ways of conceptualizing it. Broadly, a sustainable city can be understood as an approach to practically applying the knowledge about sustainability to the planning and design of existing and new cities. It represents an approach to sustainable urban development, which is a strategic process to achieve the long–term goals of urban sustainability. Accordingly, it needs to balance between the environmental, economic, and social dimensions of sustainability.

As an integrated process of change, a sustainable city strives to maximize the efficiency of energy and material use, minimize waste generation, support renewable energy production and consumption, promote carbon–neutrality, reduce pollution, provide efficient and sustainable transport, emphasize compactness, support design scalability and spatial proximity, preserve ecosystems and green space, and to promote livability and community–oriented human environments (Bibri and Krgostie 2017a).

There are different approaches to sustainable cities, which tend to be identified as models of sustainable urban form. These include compact cities, eco–cities, new urbanism, urban containment (Jabareen 2006), landscape ecological urbanism (landscape architecture and urban ecology (Steiner 2011; Kuitert 2013), and so on. Compact cities and eco-cities are the central paradigms of sustainable urbanism and the most prevalent and advocated models of sustainable urban form. Compact cities and eco-cities are the central paradigms of sustainable urbanism and the most prevalent and advocated models of sustainable urban form. Williams et al. (2000, p. 355) conclude that sustainable urban forms are “characterized by compactness (in various forms), mix of uses and interconnected street layouts, supported by strong public transport networks, environmental controls and high standards of urban management.” This characterization implies more or less a combination of the dimensions of compact cities and eco–cities. With respect to the second strand of this characterization, management is at the heart of many models of the eco–city, unlike the compact city where the form is at the core of compaction strategies (Bibri 2020a, b). The eco-city is about how the urban landscape is organized and steered rather than the spatial pattern of the characteristic physical objects in the city. In fact, these two models of sustainable urban form share several concepts, ideas, and visions. According to Roseland (1997) and Harvey (2011), a desirable eco–city has a well–designed urban layout that promotes walkability, biking, and the use of public transportation system; ensures decent and affordable housing for all socio–economic and ethic groups; and supports future expansion and progress over time. These dimensions are at the heart of the compact city in terms of sustainable transportation and mixed land use strategies.

2.1.2. Compact cities

There is no definite definition of the compact city in the literature, despite the general consensus on its common dimensions. To Burton (2002), the so-called compact city is taken to mean "a relatively high–density, mixed–use city, based on an efficient public transport system and dimensions that encourage walking and cycling." According to other views (e.g., Jenks, Burton and Williams 1996a, b; Williams, Burton and Jenks 2000), the compact city is characterized by high–density and mixed land use with no sprawl. Dantzig and Saaty (1973) provide an explanation of the densification characteristics based on three elements: the urban form, the space, and the social functions (Table 2.1).

Urban form features	Spatial features	Social functions
• High dense settlements • Less dependence on automobile • Clear boundary from surrounding areas	• Mixed land use • Diversity of life • Clear identity	• Social fairness • Self-sufficiency of daily life • Independence of government

Table 2.1: Densification characteristics

The compact city is the most advocated model of sustainable urban form due to its ability to deliver the expected benefits of environmental, economic, and social sustainability, yet to varying degrees. So, when strategically planned and well–designed, the compact city becomes able to support the balancing of the three goals of sustainability through such design strategies as compactness, density, multidimensional mixed-land use, sustainable transformation, and green open spaces (e.g., Burton 2002; Hofstad 2012; Jenks and Jones 2010; OCED 2012).

2.1.3. Eco-Cities

The idea of the eco–city is widely varied in conceptualization and operationalization. In other words, there are multiple definitions of the eco–city, depending on the context where it is embedded in the form of urban projects and initiatives in terms of the practices and strategies adopted to achieve the goals of the eco-city. Broadly, an eco–city is a human settlement which emphasizes the self–sustaining resilient structure and function of natural environment and ecosystems. It seeks to provide a healthy and livable human environment without consuming more renewable resources than it can produce or replace. Register (2002) defines an eco-city as "an urban environmental system in which input (of resources) and output (of waste) are minimized." Joss (2011) describes it based on three analytical categories: an eco–city must be (1) a development on a substantial scale, (2) occurring across multiple domains, and (3) supported by policy processes. Jabareen (2006, p. 47) describes the eco–city as an umbrella metaphor that encompasses "a wide range of urban–ecological proposals that aim to achieve urban sustainability. These approaches propose a wide range of environmental, social, and institutional policies that are directed to managing urban spaces to achieve sustainability."

The eco-city focuses more on the environmental dimension of sustainability in terms of the natural environment and ecosystems than on the economic and social dimensions of sustainability (e.g., Bibri 2020b; Mostafavi and Doherty 2010; Holmstedt et al. 2017; Rapoport and Verney 2011). There are many models of the eco–city according to an extensive literature review conducted by Bibri (2020c). These models can be caterogarized into three types: type 1 emphasizes passive solar design, type 2 combines passive solar design and greening, and type 3 focuses on green energy technologies and/or smart energy and environmental technologies (Table 2.2).

Type 1	Type 2	Type 3
• Eco-village • Solar city • Solar village • Cohousing	• Eco–City • Eco–District • Environmental City • Green City • Garden City • Sustainable Neighborhood • Living Machines	• SymbioCity • Carbon Neutral City • Zero Energy City • Zero Carbon City • Low Carbon City • Ubiquitous Eco–City • Smart Eco–City • Data-Driven Smart Eco-City

Table 2.2: Three types of eco-city models
Source: Bibri (2020c)

2.1.4. Smart Cities

It is difficult to identify common trends of smart cities at the global level. The smart city concept is still without a universally agreed definition, albeit its worldwide prevalence. Moreover, despite the wide use of the concept and its operationalization in many cities today, there still is an obscure and inconsistent understanding of what it means. The concept having different connotations and being approached from a variety of perspectives is clearly manifested in the various ways in which many governments set initiatives or implement projects to enable their cities to become, badge, or regenerate themselves as smart. All in all, a large number and variety of definitions (e.g., Albino et al. 2015) have been suggested with different emphases. Table 2.3 shows a selected set of more definitions of the smart city that adds further emphases to the concept.

Different emphases of smart city definitions
"A smart city is 'a city in which ICT is merged with traditional infrastructures, coordinated and integrated using new digital technologies" (Batty et al. 2012, p. 481).
"Connecting the physical infrastructure, the IT infrastructure, the social infrastructure, and the business infrastructure to leverage the collective intelligence of the city… A city striving to make itself "smarter" (more efficient, sustainable, equitable, and livable" (Chourabi et al. 2012, p. 2292).
"A smart city is a very broad concept, which includes not only physical infrastructure but also human and social factor" (Neirotti et al. 2014, p. 27)
"Smart cities is a term…that describe cities that, on the one hand, are increasingly composed of and monitored by pervasive and ubiquitous computing and, on the other, whose economy and governance is being driven by innovation, creativity and entrepreneurship, enacted by smart people" (Kitchin 2014, p. 1).
"A smart city is…a city which invests in ICT enhanced governance and participatory processes to define appropriate public service and transportation investments that can ensure sustainable socio–economic development, enhanced quality–of–life, and intelligent management of natural resources" (Al Nuaimi et al. 2015, p 3).
"As presently understood, a smart city is one that strategically uses networked infrastructure and associated big data and data analytics to produce a: *smart economy…*; *smart government…*; *smart mobility…*; *smart environments…*; *smart living…*; and *smart people…*" (Kitchin 2015, p. 8).
"A smart city can be described as a city that is increasingly composed of, and monitored and operated by, various forms of pervasive computing, as well as whose planning and governance are driven by innovation as enacted by various stakeholders that capitalise on and exploit cutting–edge technologies in their endeavors and practices…. A smart city can also be taken to mean a technologically and data–analytically advanced city that is able to monitor and understand its environment and citizens and explore and analyze various forms of data to generate useful knowledge in the form of applied intelligence that can immediately be used to solve different kinds of problems, or to make changes to improve the quality of life and the health of the city" (Bibri 2019, p. 11).

Table 2.3: Definitions of smart cities

Furthermore, based on a recent survey on the field of smart cities (Bibri and Krogstie 2017a), there are two main approaches to smart city: (1) the technology–oriented approach, i.e., infrastructures, architectures, platforms, systems, applications, and models and (2) the people–oriented approach, i.e., stakeholders, citizens, knowledge, services, and related data. Also, Nam and Pardo (2011) conceptualize the smart city with the dimensions of technology, people, and institutions. To gain a broad understanding of the concept of smart city, the interested reader might be directed to Song et al. (2017) who provide a detailed overview of the foundations, principles, and applications of smart cities.

It is of relevance to highlight some of the literature focusing on the defining role of ICT as well as human and social capital in smart cities in relation to the dimensions of sustainability (e.g., Anthopoulos 2017; Batty et al. 2012; Bibri 2019; Giffinger et al. 2007; Hollands 2008; Nam and Pardo 2011; Neirotti et al. 2014). This strand of research is concerned with smart cities as urban innovations that are aimed at advancing, harnessing, and integrating physical, human, and social infrastructures for environmental protection, economic regeneration, and enhanced public and social services. One of the most cited definitions of the smart city concept, which is advanced by Caragliu, Del Bo and Nijkamp (2009, p. 6), states that a city is smart "when investments in human and social capital and traditional (transport) and modern (ICT) communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory governance." As an extension of this definition, Pérez–Martínez et al. (2013, cited in Ahvenniemi et al. 2017) describe smart cities as "cities strongly founded on ICT that invest in human and social capital to improve the quality of life of their citizens by fostering economic growth, participatory governance, wise management of resources, sustainability, and efficient mobility, whilst they guarantee the privacy and security of the citizens." In this line of thinking, Batty et al. (2012, pp. 481–482) describe smart cities as cities in which “intelligence functions...are able to integrate and synthesise…these [urban] data to some purpose, ways of improving the efficiency, equity, sustainability, and quality of life in cities.” Stübinger and Schneider (2020) provide a systematic literature review on the area of smart city using a data-driven approach. They reveal that smart sustainability will come to the fore in the next years—this fact confirms the current trend as minimizing the required input of energy, water, waste, heat output, and air pollution is becoming increasingly important.

There are a number of approaches to, or frameworks for, smart cities (see Bibri, 2019a for a detailed review), as well as to smarter cities, including smart cities of the future (e.g., Batty et al. 2012), ubiquitous cities (e.g., Shin 2009), ambient cities (e.g., Böhlen 2009), sentient cities (e.g., Thrift 2014), real-time cities (e.g., Kitchin 2014), and data-driven cities (e.g., Nikitin et al 2016). The latter approach is one of the recent faces of smarter cities.

All in all, a smart city is an innovative city that focuses on developing and implementing advanced ICT in all of its systems and domains, and accordingly perform in a forward–looking, strategic, and participatory way to enhance the effects of its strategies on the basis of the intelligent combination of the endowments and activities of independent and aware citizens together with other stakeholders (organisations, institutions, industries, enterprises, and communities). This is to ensure and maintain socio–economic development, the quality of life, the efficiency of service delivery, the intelligent management of natural resources, and the optimized operation of infrastructures and facilities—ideally in line with the fundamental goals of sustainable development.

2.1.5. Data-Driven Cities

The data-driven city is one of the recent faces and future forms of smart cities. As such, it represents an emerging paradigm of smart urbanism. It is too often associated with “smarterness” under what is labeled “data-driven smart cities.” This is due to the fact that big data technology is an advanced area of ICT, which is an enabler of all approaches to smarter cities, such as ambient city, sentient city, ubiquitous city, and real-time city.

There is no definite definition or a single conceptual unit of a data-driven city, nor is there an agreed industry or academic description thereof. In a broader sense, the data-driven city is a city that implements datafication for enhancing and optimizing its operations, functions, services, strategies, and policies to some purpose. The concept employs big data analytics technologies to bring about changes to city life, which are for the better. The phenomenon of the data-driven city has materialized as a result of the emergence of big data science and computing and the wider adoption of the underlying technologies, the explosive growth of urban data, and the transformation of urban landscape in the light of urbanization. These developments can be used in a range of proposals for a conceptual framework for the data-driven city. For example, Nikitin et al. (2016) use a notion that embraces the basic elements used in the management of the data-driven city, namely data, processing technologies, and government agencies in regard to such domains as transport, utilities, environment, healthcare, education, citizen participation, and security. Accordingly, the authors describe the data-driven city as a city that is characterized by the ability of city management agencies to use technologies for data generation, processing, and analysis aimed at the adoption of solutions for improving the living standards of citizens thanks to the development of social, economic and ecological areas of urban environment. Overall, the data-driven city is digitally instrumented, datafied, and networked for enabling large-scale computation to enhance decision making processes across various urban domains for enhancing and optimizing operational management and planning development in line with the environmental, economic, and social aspects of sustainability.

2.1.6. Smart Sustainable Cities

The concept of the smart sustainable city has emerged as a result of three important global shifts at play today across the world, namely the diffusion of sustainability, the spread of urbanization, and the rise of ICT. As echoed by Höjer and Wangel (2015), the interlinked development of sustainability, urbanization, and ICT has recently converged under what is labeled “smart sustainable cities.” This currently leading paradigm of urbanism has materialized around the mid-2010s (Bibri and Krogstie 2017a). It revolves around the idea of leveraging the convergence, ubiquity, and potential of ICT of pervasive computing in the transition towards sustainability in an increasingly urbanized world. Therefore, it has gained traction and prevalence worldwide as a promising response to the imminent challenges of sustainability and urbanization. It is being embraced as an academic pursuit and societal strategy in different parts of the world, evolving into a scholarly and realist enterprise, not least within the ecologically and technologically advanced nations. In a nutshell, the concept of smart sustainable cities has become the center of attention among research institutes, universities, governments, policymakers, businesses, industries, consultancies, and communities.

The term “smart sustainable city,” is used to describe a city that is supported by the pervasive presence and massive use of advanced ICT, which, in connection with various urban systems and domains and how these are complexly integrated and intricately coordinated, respectively, enables the city to control available resources safely, sustainably, and efficiently to improve economic and societal outcomes. The integration of smart cities and sustainable cities has been less explored and underdeveloped, both conceptually and empirically due to the multiplicity and diversity of the existing definitions of smart cities and sustainable cities. ITU (2014) defines a smart sustainable city as “an innovative city that uses ICT and other means to improve the quality of life, efficiency of urban operation and services, and competitiveness while ensuring that it meets the needs of present and future gen- erations with respect to economic, social and environmental aspects.” Another close definition put forth by Höjer and Wangel (2015, p. 10) states: “a smart sustainable city is a city that meets the needs of its present inhabitants without compromising the ability for other people or future generations to meet their needs, and thus, does not exceed local or planetary environmental limitations, and where this is supported by ICT.” This entails unlocking and exploiting the potential of ICT of pervasive computing as an enabling, integrative, and constitutive technology with embodied transformational, substantive, and disruptive effects for producing the environmental, social, and economic benefits of sustainability. From a socio-technical perspective, We define a smart sustainable city as a social fabric and web made of a complex set of networks of relations between various synergistic clusters of urban entities that, in taking a holistic perspective, converge on a common approach into developing, implementing, and applying smart technologies to create and disseminate the innovative solutions and sophisticated approaches that improve and advance sustainability. In view of that, smart sustainable cities are complex systems par excellence, more than the sum of their parts and developed through a multitude of individual and collective decisions from the bottom up to the top down. They are also inherently intricate through the very technologies being used to monitor, understand, and analyze them to improve their contribution to sustainability in the face of the escalating urbanization trend.

There are many approaches to smart sustainable cities apart from the data-driven approach and its integration with the compact and ecological approaches, which is the main focus of the PhD study. These approaches depend on the strategies that the cities badging or regenerating themselves as smart sustainable prioritize with respect to applied technology solutions and sustainability dimensions based on the kind of challenges they deal with (see, e.g., Al-Nasrawi et al. 2015; Kramers et al. 2016; Martin et al. 2018; Noori et al. 2020; Pozdniakova 2018; Seçkiner Bingöl 2021).

2.1.7. Data-Driven Smart Sustainable Cities

In the PhD study, smart sustainable cities as an integrated and holistic model of urbanism is approached from the perspective of combining and integrating the strengths of sustainable cities and smart cities and harnessing the synergies of their strategies and solutions in ways that enable sustainable cities to improve, advance, and maintain their contribution to the goals of sustainability on the basis of the innovative data-driven technologies offered by smart cities. We define a data–driven smart sustainable city as a city that is increasingly composed of and monitored by ICT of pervasive and ubiquitous computing and thus has the ability to use the IoT and big data technologies to generate, process, analyze, and harness urban data for the purpose of creating deeper insights that can be leveraged to make strategic decisions that accurately address the problems and issues related to sustainability and urbanization.

The data-driven solutions can be adopted by city management agencies as well as planning and policy offices to improve sustainability, efficiency, resilience, equity, and the quality of life. Furthermore, underlying the data-driven smart sustainable city is a number of technical and institutional competences, namely:

- Horizontal information systems
- Operations centers and dashboards
- Research and innovation centers
- Educational centers and training programs
- Strategic planning and policy centers

These competences relate to the degree of the readiness of the city to introduce data-driven technology in its management as well as to the degree of the implementation of applied technology solutions in its management. The degree of readiness is characterized by the availability and development level of the technological infrastructure and competencies needed to generate, transmit, analyze, and visualize data. The degree of implementation demonstrates the extensive use of the applied technology solutions in city operational management and development planning in relation to the different areas of sustainability.

The emerging data–driven smart solutions have become of paramount importance to smart sustainable urbanism as a set of processes and practices. One key aspect of this is the use of urban data as the evidence base for formulating urban policies, plans, strategies, and programs themselves, as well as for tracking their effectiveness and modelling and simulating future urban development projects. In addition, the operation and organization of urban systems and the coordination of urban domains require not only the use of complex interdisciplinary knowledge, but also the application of sophisticated mechanisms and powerful engineering solutions underpinned by advanced computational analytics.

2.2. Overview of Sustainable Cities

2.2.1. Compact Cities and Eco-cities: Shortcomings and Deficiencies

Sustainable development has undoubtedly inspired a whole generation of urban scholars and practitioners into a quest for the tremendous opportunities that could be explored by, and the enormous benefits that could be realized from, the planning and design of the existing models of sustainable urban forms, notably compact cities and eco-cities. Sustainable urban development is seen as one of the keys towards unlocking the quest for a sustainable society. Therefore, it is promoted by global, national, and local policies alike as the most preferred response to the challenges of sustainable development. Compact cities and eco-cities are the central paradigms of sustainable urban development and the most prevalent and advocated models of sustainable cities. Numerous recent national and international policy reports and papers state that these two models contribute, though to varying degrees, to resource efficiency and reliability, environmental protection, socio-economic development, social cohesion and inclusion, quality of life and well-being, and cultural enhancement. It is argued that the compact city model is able to contribute to and support the balancing of the three goals of sustainability (e.g., Burton 2002; Jenks and Dempsey 2005; Hofstad 2012; Jenks and Jones 2010; OCED 2012), and that the eco–city model is able to achieve the goals of environmental sustainability and to produce some economic and social benefits of sustainability (e.g., Joss 2010; Joss, Cowley and Tomozeiu 2013; Kenworthy 2006; Rapoport and Vernay 2011; Suzuki et al. 2010). While the environmental goals of sustainability tend to dominate in the discourse of the eco-city (e.g., Mostafavi and Doherty 2010; Holmstedt et al. 2017), the discourse of the compact city emphasizes the economic goals of sustainability (e.g., Hofstad 2012; Jenks and Jones 2010), with the social goals of sustainability being of less focus in the eco-city than in the compact city (e.g., Bibri 2020a, b; Lim and Kain 2016; Heinonen and Junnila 2011; Bramley and Power 2009; Raporport and Verney 2011). Bibri (2020c) provides a comprehensive state–of–the–art review of compact urbanism as a set of planning and development practices and strategies, focusing on the three dimensions of sustainability and the significant, yet untapped, potential of big data technology for enhancing such practices and strategies under what is labelled "data–driven smart sustainable urbanism." The author also critically discusses compact urbanism from the perspective of Science, Technology, and Society (STS). Bibri (2020b) provides a state–of–the–art review of the field of ecological urbanism in terms of foundations, models, strategies, research issues and gaps, as well as data–driven smart technological trends. In his article "Sustainable Urban Forms Their Typologies, Models, and Concepts," Jabareen (2006) addresses the question of whether certain urban forms contribute more than others to sustainability, and subsequently proposes a matrix of sustainable urban forms to help assess their contribution to sustainability with respect to planning.

In light of the above, however, it is of high relevance and importance to integrate the compact city and eco-city models so as to consolidate and harness their design strategies and sustainable solutions to deliver the best outcomes of sustainability. Their integration is indeed justified by the fact that the compact city needs to enhance its environmental performance, that the eco-city needs to improve its social performance, and that both contribute differently to economic sustainability, with the former focusing on mixed-land use strategy and the latter on green-tech innovation strategy. Another argument supporting their integration is that they have already many overlaps among them in their ideas and concepts, as well as in their principles and policies. In short, the two models of sustainable urban form are compatible and not mutually exclusive, with some distinctive concepts and key differences. Some of the attempts that have been undertaken to integrate these models tend to provide ideal approaches, simply combine some ideas from each one of them to form new loosely integrated models, or strengthening one model through adding principles from the other, all with the objective to enhance some missing aspects of sustainability (e.g., Farr 2008; Harvey 2011; Jabareen 2006; Kenworthy 2019; Marcotullio 2017; Roseland 1997; Suzuki et al. 2010). However, as this work is more often than not based on design with respect to the discipline of architecture and planning, it tends to emphasize more on creativity, common sense, ideal target pursuit, and future scenarios, rather than fact-based evidence explanation, empirically grounded research, or scientific finding-oriented exploration.

Regardless, emphasizing one of the dimensions of sustainability remains a shortcoming (failure to meet certain standards in plans) and deficiency (lacking some necessary elements) in the urban context. Indeed, urban sustainability is a holistic approach to thinking, meaning that all the three dimensions of sustainability are equally important. Within the "sustainable urban form" debate, the idea of the "compact city" has been favoured, above other settlement patterns [such as the eco-city], in policy for a number of decades, although with less agreement by researchers in the field (Williams 2010). Yet the debates about them are rarely understood outside their expert communities. Holmstedt, Brandt and Robert (2017) point out that implementing sustainable solutions in the context of the eco-city is more difficult because no unified practical definition is still accepted even if the subject of sustainability has been hotly debated over the last four decades, and most projects act dishonesty in order to gain an advantage by not defining what is meant by sustainability and not meeting all its requirements. The concept of the eco–city has, in policymaking and planning, tended to focus mainly on the underling structure of urban metabolism—sewage, water, energy, and waste within the city (Höjer and Wangel 2015), falling short in considering economic and social issues.

2.2.2. Sustainable Urban Forms: Problems, Issues, and Challenges

The form of the contemporary city has been a salient factor for enacting cities that are more sustainable, efficient, equitable, and livable. It was the widespread diffusion of sustainable development in the early 1990s that gave a major stimulus to the question regarding the contribution that certain urban forms as human settlements might make to sustainability. Sustainable development continues to stimulate the discussion and provoke thoughts about the form of the city in light of the mounting challenges facing the world and the societal transformations triggered by the advances in science and technology. Besides, the rate and scale of urbanization will escalate over the coming years, and consequently, sustainable cities will face new challenges, including creating cost-efficient environments, improving life quality for citizens, maintaining economic growth, and being able to handle non-static and complex concepts that evolve over time. In the current climate of the unprecedented urbanization of the world, it has become even more challenging for sustainable cities to reconfigure themselves more sustainably without the use of advanced ICT (Bibri and Krogstie 2021). Therefore, policymakers, planners, and mangers within the ecologically advanced nations, or those countries that are known for their high level of sustainable development practices, need to promote, develop, and implement innovative solutions for operational management and sophisticated approaches to development planning to contain the negative effects of urbanization.

The intractable issues engendered and special conundrums posed by urban growth exacerbate the wicked problems already characterizing sustainable cities as complex systems. The consequences of urbanization are associated with intensive energy consumption, poor water quality, air and noise pollution, public health decrease, toxic waste disposal, resource depletion, poor housing and working conditions, saturated transport networks, traffic congestion, social inequalities, socio-economic disparities, and inefficient management of outdated infrastructures. Urban growth may jeapordize the sustainability of sustainable cities as it puts an enormous strain on urban systems and great demand on natural resources and ecosystem services. Especially, the experience of the past decades has shown that the conventional approaches to urban planning and development based on interventions promoting renewed access to urban life have been inadequate to cope with the adverse impacts of urbanization, high population growth, and rapid changes facing sustainable cities. All in all, new circumstances require new responses concerning the development planning and operational management of sustainable cities in order to be able to respond to the changes in socio-economic needs of citizens and to tackle the environmental pressures on urban environments, as well as to keep up with societal transitions and global trends.

Moreover, yet knowing if we are actually making any progress towards sustainable cities is problematic. There is a very contradictory, conflicting, and fragmented picture that arises of change on the ground. Given these complex conditions, it is sometimes hard to see where the common challenges of sustainable cities may be identified. What lies at the heart of these challenges is the conceptualization of sustainable cities with regard to their progress. This pertains to the kind of changes that need to be made and to how progress can be assessed when it comes to developing or enhancing models of sustainable urbanism. Indeed, producing theoretically and practically robust models of sustainable urban form has been one of the most significant intellectual and practical challenges since the early 1990s (e.g., Bibri and Krogstie 2017b Jabareen 2006; Kärrholm 2011; Neuman 2005; Williams 2010). As concluded by Jabareen (2006, p. 48), "neither academics nor real-world cities have yet developed convincing models of sustainable urban form and have not yet gotten specific enough in terms of the components of such form." This implies that it has been very difficult to translate sustainability into the built form of cities. Indeed, sustainable urban forms epitomize complex systems par excellence, more than the sum of their parts and developed through a multitude of individual and collective decisions from the bottom up to the top down. As such, they are full of contestations, conflicts, and contingencies that are not easily captured, steered, and predicted respectively. In a nutshell, they are characterized by "wicked problems" (Rittel and Webber 1973). This means that the physical, environmental, economic, and social problems of sustainable cities are difficult to define, unpredictable, and defying standard principles of science and rational decision–making. As a consequence, when tackling wicked problems, they become worse due to the unforeseen consequences which were overlooked because of treating the system under study in too immediate and simplistic terms, or failing to approach that system from a holistic perspective. Rittel and Webber (1973) argue that the essential character of wicked problems is that they cannot be solved in practice by a central planner. Wicked problems are so complex and dependent on so many intertwined factors that it is hard to grasp what they exactly are and thus how to tackle them. Therefore, it is impossible to plan sustainable cities as urban complexities due to the lack of a complete form of knowledge of the consequences of interventions, which is evidently impossible (Marshal 2012).

Furthermore, it is difficult to evaluate the extent to which the existing models of sustainable urban form contribute to sustainability. Indeed, it is not evident which of these models is more sustainable, although there seems to be a consensus on topics of relevance to sustainability within research on sustainable urban forms. There is a lack of agreement about the most desirable urban form in the context of sustainability (e.g., Bibri and Krogstie 2017a, b; Jabareen 2006; Williams, Burton, and Jenks 2000). As a result, city governments, planning experts, and landscape architects are grappling with the dimensions of the existing models of sustainable urban form by means of a variety of planning, design, and policy approaches. What is known about the relationship between planning and design interventions and sustainability goals is a subject of much debate. This means that realizing sustainable urban forms require making countless decisions and complex negotiations about urban form, ecological design, urban design, sustainable technologies, policy measures, and governance arrangements. Moreover, the conflicts and contradictions associated with sustainable urban development thinking and practice will continue without conceptual anchor (Williams 2010).

In addition, it is not an easy task to judge whether or not a certain sustainable urban form is actually sustainable, irrespective of the spatial scale at which such form may be considered. To some extent, the problem relates to the dilemma of form and function or structure and process, and the way this dichotomy has been conceived and approached, i.e., set up a relationship between cause and effect. New urbanism "is by necessity a fully planned and regulated environment, fiercely resistant to change and a fully a fully planned and regulated environment, fiercely resistant to change and any deviation from the rigid rules that govern its form and function. But it is precisely this inflexibility, which is so important in its struggle for completion as a development enterprise" (Durack 2001, p. 64). However, Neuman (2005, p. 23) argues that the form of the city is "both the structure that shapes process and the structure that emerges from a process." It follows that if form "is an outcome of evolution" (Neuman 2005, p. 23), then the arrangement of how to undertake planning in ways that support and guide such an evolutionary process becomes a key issue. This implies reversing the focus on urban forms governed by static planning due to its inherent limitations in achieving the goals of sustainability. Durack (2001) argues for open, indeterminate planning due to its advantages, namely, cultural diversity; tolerance and value of topographic, social, and economic discontinuities; citizen participation; and continuous adaptation, which is common to human settlements like all other living organisms and systems.

The stable relationships between a set of sustainable activities and a certain urban form are not easily generalizable on the basis of form–function (Kärrholm 2011). It is widely acknowledged that the integration and balancing of the dimensions of sustainability is conflicting and contradictory, as the different aspects of sustainability rely on the different criteria for desirable outcomes. Consequently, planners will in the upcoming years "confront deep-seated conflicts among economic, social, and environmental interests that cannot be wished away through admittedly appealing images of a community in harmony with nature." (Campbell 1996, p. 9) Such conflicts also involve spatial interests. Focusing on the urban scale, Kärrholm (2011) sheds more light on tendencies toward scale stabilization, i.e., the tendencies of planning from the perspective of only one or a few pre-fixed scales. The same endeavor to apply sustainable development to urban form might increase one aspect of sustainability (e.g., environmental) on one scale (e.g., the urban) while decreasing it on another (e.g., neighborhood).

Indeed, research in the field of sustainable urban form, especially compact cities and eco-cities, has, over the last two decades, produced contradictory, uncertain, weak, non-conclusive, and questionable results (e.g., Bibri 2020a, b, c; Cugurullo 2016; Kaido 2005; Kärrholm 2011; Lim and Kain 2016; Neuman 2005; Williams 2010). The overall outcome of this research relates mostly to the actual benefits and effects claimed to be delivered by the design strategies adopted as part of the planning of sustainable cities. In a nutshell, the issue of sustainable urban form has, both in discourse and practice, been problematic. Much of what we know about sustainable cities to date has been gleaned from studies that are characterized by data scarcity and employ traditional data collection and analysis methods with inherent limitations, biases, and constraints, often as a result of relying on selective samples (Bibri and Krogstie 2018). This adds to the focus on long-term approaches to city planning, the inability of simulation models to address the current conceptions of the city as a complex system in terms of its future design, and the inefficient mechanisms used in city operational management. It follows that most of the inadequacies, shortcomings, struggles, and bottlenecks related to sustainable urban forms are due to how these human settlements have been studied, understood, planned, designed, and managed for several decades. We still know very little about the majority of human settlements.

The model of the city is no longer predicated on the basis that the city is a stable unchanging structure, but rather one that is more and more dominated by information flows, with no physical traces, reflecting the complexity of socio-economic and technical processes occurring in urban spaces and the unpredictability of various internal and external factors. This brings us to the issue of conceiving cities in terms of forms and pre-fixed scales as being inadequate to achieve the goals of sustainable development. Rather, urban forms and their spatial scaling should be conceived in terms of the outcomes of the processes of urbanization. This conception holds significant potential for attaining the elusive goals of sustainable development, as it enables sustainable urban forms together with their spatial scaling to be dynamic in planning, scalable in design, and efficient in operational functioning. This indeed raises the right questions of whether and to what extent the processes of building, scaling, and expanding the city and the processes of living, consuming, producing, and moving in the city are sustainable. Besides, a well–established fact is that cities as complex systems evolve and change dynamically, and the underlying theoretical and practical knowledge of planning and design should respond accordingly. This calls for advanced technologies and their novel applications in order to respond to urban growth, environmental pressures, changes in socio–economic needs caused by urbanization, among others. Especially, there is a symbiotic relationship between urbanization and ICT.

The problems, issues, and challenges facing sustainable cities are more complex due to the increasing flows and channels of information, the divergence of agents, the heterogeneity of actors, the prevailing processes of globalization, the dispersion of power, and the difficulty of decision making. This is drastically changing thanks to the clear potential and substantive effects of big data technologies on urban studies, urban analytics, urban processes, and urban practices. The abundance of urban data, coupled with their analytical power, opens up for new opportunities for innovation in sustainable cities, particularly in relation to linking their infrastructures to their operational functioning and planning through control, optimization, management, and improvements, and thus tightly interlinking and integrating their systems and domains. Unlocking the potential of urban data and leveraging it in the transition towards sustainability implies addressing and overcoming the problems, issues, and challenges facing sustainable cities in their endeavor to achieve the long-term goals of sustainability. The United Nations's 2030 Agenda regards advanced ICT as a means to promote socio–economic development and protect the environment, increase resource efficiency, achieve human progress and knowledge in societies, upgrade legacy infrastructure, and retrofit industries based on sustainable design principles (United Nations 2015b).

Indeed, it has been argued that sustainable cities need to embrace and leverage what smart cities have to offer in terms of advanced technology solutions so as to achieve the desired outcomes of sustainability under what is labelled "data-driven smart sustainable cities." This brings us to the question related to the weak connection between sustainable cities and smart cities as approaches and their extreme fragmentation as landscapes at the technical and policy levels, adding to their opposite conceptual characteristics and existing tensions (see Bibri 2021a for a detailed review).

2.3. Overview of Smart Sustainable Cities and their Data-Driven Dimension

2.3.1. Emerging Global Trends and Technological Shifts

As with all paradigms of urbanism, data–driven smart sustainable cities have emerged and materialized as a result of an amalgam of several forms of prevailing and emerging trends (Table 2.4). These will also shape and drive the expansion, success, and evolution of this new paradigm of urbanism. They reflect a congeries of global and societal forces behind it in the era of big data.

Forms of Trends	Prevailing and Emerging Trends
Global trends	Sustainability, ICT, urbanization, and globalization
Academic discourses	Sustainable urbanism, compact urbanism, ecological urbanism, smart urbanism, data-driven urbanism, scientific urbanism, and sustainable urban development
Urbanism paradigms:	Sustainable cities, smart cities, smart sustainable cities, and data-driven smart sustainable cities
Computing paradigms	Ubiquitous computing, sentient computing, the IoT, big data computing, quantum computing, cloud computing, fog computing, edge computing, and distributed computing
Scientific paradigms	Data–intensive science (data-driven science and empiricism), big data science, empirical evidence, scientific theory, and computational science
Technological trends	Bg data analytics, the IoT sensing, Artificial Intelligence, datafication, Blockchain, virtual reality, and 5G

Table 2.4: Prevailing and emerging trends behind data-driven smart sustainable cities

Sustainable cities are undergoing unprecedented transformative changes in response to the recent scientific paradigm shift and technological innovations brought on by big data science and analytics that will change sustainable urbanism in fundamental and irreversible ways. Transforming sustainable cities is increasingly justified by the need for monitoring, analyzing, planning, and managing the different types of their infrastructures and systems in more innovative ways to achieve the desired outcomes of sustainability. There is a growing perception that the centripetal movement of smart sustainable interests and ideas in urban practices, ICT innovations, and institutional developments can have a significant impact on smart sustainable–induced processes of transformation in the primary operations, core functions, and central institutions of modern society. Besides, the ongoing quest and growing motivation for achieving the SDG 11 has increased the need to understand and manage sustainable cities in new and innovative ways (United Nations 2015a), particularly in response to urbanization and in anticipation of its unintended effects. Nonetheless, urbanization also creates enormous environmental, social, economic, and spatial changes, which provide an opportunity for sustainability with the potential to apply advanced technologies so to use resources more efficiently and control them more safely, to promote more sustainable land use, and to preserve the biodiversity of natural ecosystems and reduce pressure on their services, with the ultimate aim to improve economic and societal outcomes.

Smart sustainable cities are about recognizing the link between the major trends shaping modern society at a growing pace, namely the rise of advanced ICT, the escalating rate of urbanization, and the widespread diffusion of sustainability development. This entails finding ways to unlock the potentials and explore the opportunities of interlinking these developments for reaching the long-term vision of sustainability. Against the backdrop of the complex challenges of sustainable development and the negative consequences of urbanization facing sustainable cities, a number of new and innovative ways of understanding, planning, designing, and managing sustainable cities based on advanced ICT have materialized and are rapidly evolving and making their way to practice. There is an increasing recognition that advanced ICT constitutes a promising response to the challenges of sustainable urban development due to its tremendous, yet untapped, potential for solving many environmental and socio-economic problems and issues. Both sustainable urbanism and smart urbanism as approaches to sustainable urban development emphasize particularly the role and potential of big data technologies as an advanced form of ICT in improving and advancing sustainability through innovative operational management mechanisms and development planning approaches.

2.3.2. Emerging Operational Management and Development Planning Solutions

All traditional mechanisms of city management (administration, organization, and planning) are gradually replaced with digital mechanisms enabling and supporting data-driven decision making. Big data analytics improves the quality and speed of decision making. Data-based city management relies on urban computing and intelligence for implementing the data-driven technology solutions developed for the various spheres of city administration, including, but not limited, to:

- Transport management
- Traffic management
- Street lighting management
- Mobility management
- Waste management
- Energy management
- Environmental monitoring
- Building management
- Public safety
- Healthcare and education

Urban computing and intelligence bridges the gap of ubiquitous sensing, intelligent computing, cooperative communication, and large-scale data processing and management technologies to create novel solutions to enhance urban forms, urban infrastructures, urban environments, and urban services. Such solutions can be developed through cloud and fog computing or city own facilities, the IoT devices, intelligent networks, artificial intelligence, and big data analytics.

Big data technologies are heralding a new era wherein sustainable cities are morphing in response to the influence brought by the emerging paradigm of big data computing. Indeed, there has recently been a conscious push for sustainable cities across the globe to be smarter and thus more sustainable by adopting data-driven technologies to enhance and optimize their operations, functions, services, designs, strategies, and policies. This transformation—which entails new and innovative ways of how sustainable cities can be monitored, understood, analyzed, planned, and thus designed, controlled, and regulated—is manifest in the increasingly level of the development and implementation of data-driven solutions in their operational management mechanisms and development planning approaches. In fact, big data technologies have, in the context of sustainability (especially its environmental dimension), become as essential to the functioning of smart cities (e.g., Angelidou et al. 2017; Nikitin et al. 2016; Perera et al. 2017; Petrović and Kocić 2020; Thakuriah et al. 2017) as to that of sustainable cities (e.g., Pasichnyi et al. 2019; Shahrokni, Levihn and Brandt 2014; Shahrokni et al. 2014; Shahrokni et al. 2015; Späth 2017; Thornbush and Golubchikov 2019). As a result, urban processes and practices are becoming highly responsive to a form of data-driven urbanism. In other words, we are moving into an era where instrumentation, datafication, and computation are routinely pervading the very fabric of both sustainable cities and smart cities. One of the consequences of data-driven smart sustainable urbanism is that city systems and domains are becoming much more tightly interlinked and integrated. Ans also, vast troves of data are being generated, analyzed, harnessed, and exploited to understand the multiple complexities of sustainable cities so as to be able to make them safer, cleaner, more resilient, and, above all, more efficient. The intersection of complexity science and big data analytics is making it possible to reveal hidden regularities in the organization of the city. And therefore, it is allowing us to better anticipate the systemic behavior that result from the many interactions of all the components that make up the city.

Smart cities are offering advanced simulation models and optimization methods that are being embraced by sustainable cities to respond to the complexities they embody and thus to improve their performance and optimize their efficiency. This relates to urban intelligence functions, which represent new conceptions of how the city functions and utilizes and harnesses complexity science, urban complexity, sustainability science, urban sustainability, urban science, data science, and data-intensive science in constructing powerful new forms of simulation models and optimization methods that can generate urban forms, structures, and and spatial organizations. These are intended to advance sustainability, increase efficiency, improve equity, and enhance the quality of life. Bibri (2021b) provides a detailed review of the scientific disciplines associated with urban intelligence in the context of data-driven smart sustainable urbanism, as well as a framework illustrating their integration and fusion from an interdisciplinary and transdisciplinary perspective.

The sort of urban intelligence and planning functions envisaged for data-driven smart sustainable cities of the future relate to their operations, functions, services, designs, strategies, and policies. Such functions, which should evolve in the form of innovation/intelligence labs that enable urban monitoring, design, and development, include, but are not limited to:

- The efficiency of energy systems
- The efficiency of distribution networks
- The efficiency and improvement of transportation systems
- The enhancement of communication systems
- The efficiency of lighting system
- The resilience of essential urban infrastructure in terms of withstanding adverse conditions and recovering from potential shocks
- The improvement of urban metabolism
- The monitoring and control of the environment
- The efficiency and scalability of urban design
- The efficiency and enhancement of public services
- The optimal use and effective accessibility of facilities.

Data-driven smart sustainable cities need to evolve urban intelligence and planning functions in response to the emerging wave of building models of smart cities and sustainable cities functioning in real time from routinely sensed data. This is coupled with their ubiquitous sensing getting closer to providing quite useful information about longer term changes (see, e.g., Ameer and Shah 2018; Kitchin 2014; Nikitin et al. 2016; Shahrokni et al. 2015; Shahrokni Lazarevic and Brandt 2015; Sinaeepourfard et al. 2016). Further, urban intelligence functions are associated with the control, management, optimization, and enhancement associated with the operating, organizing, and planning processes of the infrastructures and services enabling the data-driven smart sustainable city of the future. They involve different data analytics components, including data sources, system components, enabling technologies, functional elements, and analytics types (i.e., descriptive analysis, diagnostic analysis, predictive analysis, prescriptive analysis, and inferential analysis). The purpose is to gather and manage data on a variety of urban systems (mobility, traffic, transport, energy, environment, water, waste, etc.), to model urban phenomena, and to provide the necessary simulation and visualisation tools to be integrated into decision support systems.

Smart sustainable cities are depicted as constellations of instruments across many scales that are connected through multiple networks characterized by high speed and intelligence, which provide continuous data regarding the different aspects of urbanity in terms of the flow of decisions about the environmental, economic, social, physical, and spatial forms of the city. These decisions are to be supported by intelligence and planning functions, which are able to integrate and synthesize urban data to some purpose, ways of improving the functioning and performance of cities. In this context, functional requirements are the heart of what the city system is expected to do and the capabilities it needs to have, whereas performance requirements are how well the city system functions with respect to improving sustainability, efficiency, resilience, equity, and the quality of life.

In general, computational and scientific approaches, especially those enabled by big data technologies, have become necessary for dealing with urban complexities in the context of sustainable urbanism and smart urbanism. Consequently, it has become of paramount importance to develop and employ sophisticated methods and innovative solutions for tackling the complex challenges facing sustainable cities in terms of development planning and operational management in the face of urbanization. This requires a blend of sciences, and big data technologies are well placed to initiate this endeavor given that their application to urban systems is founded on the integration and fusion of data science, computer science, urban science, complexity science (Batty et al. 2012; Bettencourt 2014; Homer-Dixon 2011; Kitchin 2014, 2016), sustainability science, urban sustainability, and data-intensive science (Bibri 2021b) as both theoretical and applied disciplines. And together with political and social solutions and citizen participation (Kitchin, Lauriault and McArdle 2015), they may play a key role in solving some of the wicked problems characterizing sustainable cities in term of their development planning. Rittel and Webber (1973) argue that the essential character of wicked problems is that they cannot be solved in practice by a central planner. Wicked problems are so complex and dependent on so many intertwined factors that it is hard to grasp what they exactly are, or thus how to tackle them. In other words, they are difficult to explain and impossible to solve because of incomplete, contradictory, and changing requirements that are not easy to recognize. Of practical relevance to this paper, Bettencourt (2014) reformulates some of Rittel and Webber's (1973) arguments in a modern form in what is called the "planner's problem," which has two distinct facets: (1) the knowledge problem and (2) the calculation problem. The first problem refers to the planning data needed to map and understand the current state of the city. It is conceivable that urban life and physical infrastructure could be adequately sensed in several million places at fine temporal rates, generating huge but manageable rates of information flow by the various forms of advanced ICT. It is not impossible, albeit still implausible, to conceive and develop technologies that would enable a planner to have access to detailed information about every aspect of the infrastructure, services, social lives, and environmental states in the city. The second problem refers to the computational complexity to carry out the actual task of planning in terms of the number of steps necessary to identify and assess all possible scenarios and to choose the best possible course of action. Unsurprisingly, the exhaustive approach of assessing all possible scenarios is impractical due to the fact that it entails the consideration of impossibly large spaces of possibilities. But what this reformulation does promise is an ability to provide a powerful means for envisioning and predicting future scenarios in ways that were inconceivable a decade ago.

While planning cannot reproduce the characteristics of sustainable cities that have been developed based on incremental and interactive processes involving many stakeholders over time, the primary role of big data lies in enabling information flows and channels, coordination mechanisms, cooperative communication, well-informed and evidence-based decisions, and learning and sharing processes involving divergent constituents and heterogenous collective and individual actors. In addition, the ever-increasing deluge of urban data epitomizes a sea change in the kind of data that we generate about urban systems and urban environments as regards what happens and might happen where, when, why, and how, so as to devise more effective actions and measures for urban planning and design. It has become possible to assess what is happening at any one time and to react and plan appropriately, instead of basing decisions on periodic, partial, or anecdotal evidence. Big data analytics is heralding major changes in understanding sustainability and redefining related problems and issues in new ways for better planning. In particular, it is pushing planning into short termism as regards how the city functions and can be managed, which adds a whole new dimension to sustainable urbanism by shifting away from long–term strategic planning. Short–termism in planning is about measuring, evaluating, modelling, and simulating what takes place in the city over hours, days, or months instead of years, decades, or generations. Also, big data analytics is enabling what is called joined-up planning, which relates strongly to the kind of connection, networking, system interoperability, and data integration enabled by advanced ICT as essentially network-based and enabler of an extensive interaction across many spatial scales and urban domains. Joined-up planning is a form of integration that enables the system–wide effects of environmental, economic, and social sustainability to be tracked, understood, analyzed, and built into the very designs and responses characterizing the operations and functions of the data-driven smart sustainable city of the future. Such designs and responses involve forms, structures, systems, processes, activities, and services. A number of recent studies have addressed the emerging approaches to urban planning or future urban developments in the context of smart cities and sustainable cities (e.g., Ameer and Shah 2018; Batty 2013; Bettencourt 2014; Rathore et al. 2016; Silva et al. 2018).

Smart cities are increasingly connecting the ICT infrastructure, the built infrastructure, the urban infrastructure, the social infrastructure, and the economic infrastructure to leverage their collective intelligence in becoming more efficient, sustainable, resilient, livable, and equitable. In this respect, they seek to solve a fundamental conundrum—ensure economic development, social equity, and the quality of life while optimizing energy efficiency, reducing pollution, and strengthening resilience. This has been made possible by utilizing the fast–flowing torrent of data and the core enabling and driving technologies of the IoT and big data analytics. The recent advances in urban computing and intelligence used for monitoring, understanding, analyzing, planning, and managing urban infrastructures, systems, and activities are the most significant aspects of smart cities that are being embraced and leveraged by sustainable cities in order to improve, advance, and maintain their contribution to sustainability. Urban computing and intelligence bridges the gap of ubiquitous sensing, intelligent computing, cooperative communication, and large-scale data processing and management technologies to create novel solutions to enhance and optimize urban forms, urban infrastructures, urban environments, and urban services.

For supra–national states, governments, and city officials, smart cities offer the enticing potential of environmental improvement and socio–economic development, as well as the renewal of urban centers as hubs of innovation and research (e.g., Bibri and Krogstie 2020b; Noori et al. 2020; Kitchin 2014, 2016; Nikitin et al. 2016; Trencher 2019).

In light of the above, a recent research wave has started to focus on amalgamating sustainable cities and smart cities in a variety of ways in the hopes of reaching the optimal level of sustainability under what is labelled "data-driven smart sustainable cities." This emerging paradigm of urbanism tends therefore to take several forms based on how the integrated approach to sustainable cities and smart cities can be conceptualized in research. As a corollary of this, there is a host of unexplored opportunities towards new approaches to smart sustainable urbanism. This is key to solving or mitigating the extreme fragmentation and the weak connection associated with sustainable cities and smart cities as landscapes and approaches, respectively (e.g., Ahvenniemi et al. 2017; Angelidou et al. 2017; Bibri and Krogstie 2017a; Bifulco et al. 2016; Kramers et al. 2014) through developing multiple visions of sustainable futures. Just like in the discourse of sustainable cities, where there are a number of competing visions of sustainable urbanism (Williams 2010), it is important to understand and value this multiplicity of socially constructed potential futures, rather than adopt a one-model-fits-all approach, yet with some coherence of purpose. However, the integrated approach proposed by the PhD study entails combining and integrating the strengths of sustainable cities and smart cities and harnessing the synergies of their strategies and solutions in ways that enable sustainable cities to improve, advance, and maintain their contribution to the goals of sustainability on the basis of the innovative data-driven technologies offered by smart cities, to reiterate. This is accomplished by clarifying a novel model for data-driven smart sustainable cities of the future as a vision and working towards achieving that goal.

3. Research Methodology

This chapter describes the research goal and justifies and discusses the research methodology adopted in this thesis.

3.1. Research Goal

The goal of the PhD study is to develop a novel model of urbanism—data-driven smart sustainable cities of the future—by integrating the prevailing paradigms of sustainable urbanism and the emerging paradigms of smart urbanism in terms of their dimensions, strategies, and solutions. The proposed model of urbanism, which takes the form of a strategic planning process of transformative change towards suitability, is grounded in case study research. This was carried out on a total of six of the ecologically and technologically leading cities in Europe.

3.2. Justification: Aspects, Importance, Choice, and Relevance

Generally, the fundamental aim for undertaking a research is to discover something unknown and thus, to develop and extend human knowledge. Prior to conducting the actual research process, a determining decision that is to be made is the analysis of the horizons offered by various research approaches and the clear selection of those among them that are most appropriate for achieving the kind of results that reflect to a greatest extent the research goal set.

As an emerging model of urbanism, data-driven smart sustainable cities of the future represent a new approach to sustainable urban development, a strategic process to achieve the long–term goals of urban sustainability—with the support of advanced ICT, notably data-driven technologies. The notion of urban sustainability denotes a desired (normative) state in which a city retains a balance of the socio–ecological systems. This can be achieved by adopting and executing the strategies of sustainable urban development as a desired (normative) trajectory to meet its targets and objectives. In other words, to achieve the status of sustainable cities requires improving and advancing the physical, environmental, economic, and social systems of the city over the long run—given their interdependence, synergy, and equal importance—in line with the long-term vision of sustainability. This strategic goal entails fostering linkages between scientific research, technological innovation, investment direction, policy analysis, institutional development, governance networks, planning strategies, and development projects and initiatives in relevance to sustainability. It also calls for applying an interdisciplinary approach to research. Indeed, when undertaking analysis, the perspective should be the grouping of interrelated disciplines that have an appropriate focus for investigating the particular problem, as each academic discipline opens new dimensions of knowledge.

All the above aspects and requirements are at the core of the normative backcasting approach to futures studies, which in this context facilitates and contributes to the planning, design, development, implementation, evaluation, and improvement of future cities. One of the most enticing areas of research within urban sustainability is that which is concerned with normative backcasting-oriented futures studies. These offer great opportunities for addressing long-term problems and sustainability solutions. The relevance and rationale for adopting the normative backcasting approach to the futures study stems from the strategic planning process it entails to achieve the long-term goals of urban sustainability in the form of a vision for a desired future. Backcasting is well suited to any multifaceted kind of planning process (e.g., Holmberg and Robèrt 2000) , as well as well equipped to be applied to long-term sustainability problems (e.g., Dreborg

1996; Holmberg 1998; Quist 2007; Robert et al. 2002) thanks to its goal-oriented and problem-solving character.

3.3. Methodological Framework

The methodological framework applied in the futures study combines and integrates normative backcasting and descriptive case study as qualitative approaches. The backcasting approach was employed to achieve the overall aim of the futures study. The case study approach, which is associated with the empirical phase of the futures study, was adopted to illuminate the urban phenomena of compact cities, eco-cities, data–driven smart cities, and environmentally data-driven smart sustainable cities. The methodological framework was espoused to explore the topic of data-driven smart sustainable cities of the future, a process that involves six steps, each with several guiding questions to answer (Table 3.1).

Step 1: Detail strategic problem orientation (Part 1) 1. What is the model of urbanism to be studied? 2. What are the aim, purpose, and objectives of the backcasting study in relation to this model? 3. What are the long–term targets declared by the goal–oriented backcasting approach? 4. What are the objectives these targets are translated to for backcasting analysis?
Step 2: Detail strategic problem orientation (Part 2) 1. What are the main prevailing trends and expected developments related to the model to be studied? 2. What are the key sustainability problems associated with the current model of urbanism and what are the causes? 3. How is the problem defined?
Step 3: Generate a sustainable future vision 1. What are the demands for the future vision? 2. How does the future model of urbanism look like? 3. How is the future model of urbanism different from the current model of urbanism? 4. What is the rationale for developing the future model of urbanism? 5. Which sustainability problems have been solved and which technologies have been used in the future vision?
Step 4: Conduct empirical research 1. What is the justification for the methodological framework to be adopted? 2. Which category of case study design is most relevant to investigating the dimensions of the future model of urbanism? 3. How many case studies are to be carried out and what kind of urban phenomena should they illuminate? 4. To what extent can this investigation generate new ideas and illustrate the theories applied and their effects, as well as underpin and increase the feasibility of the future vision?
Step 5: Specify and Integrate the components of the future model of urbanism 1. What urban and technological components are necessary for the future model of urbanism? 2. How can all these components be integrated into a framework for strategic sustainable urban development planning? 3. What are the key benefits, potentials, and opportunities of the future model of urbanism?
Step 6: Perform backwards–looking analysis 1. What built infrastructure changes are necessary for achieving the future vision? 2. What sustainable urban infrastructure changes are necessary? 3. What smart urban infrastructure changes are necessary? 4. What social infrastructure changes are necessary? 5. What technological infrastructure changes are necessary? 6. What institutional changes are necessary?

Table 3.1: The guiding questions for each step in the backcasting-oriented futures study

3.3.1. Backcasting as a Strategic Planning Process

The term "backcasting," which was coined by Robinson in 1982, can denote a concept, a study, a process, an approach, a methodology, a framework, or an interactive process among stakeholders. Hence, it has been defined in multiple ways within different contexts. Robinson (1990, p. 823), who coined the term, defines backcasting as a normative approach that works "backwards from a particular desired end point to the present in order to determine the feasibility of that future and what policy measures would be required to reach that point." Thus, backcasting is a planning process by which a desired outcome is envisioned and articulated, followed by the question: "what do we need to do today to reach that specified outcome?" (Figure 3.1) This question is about figuring out the "next steps," which are quite literally the next concrete actions and measures to undertake. It is as important to undertake the next steps as having lofty visions, thereby sustaining momentum by an explicit shared vision of success and being able to use that to guide the next steps. While the next steps are usually based on reacting to the present circumstances, creativity, and common sense, they are still aligned with the future vision. Unlike forecasting, which tends to present a more limited range of options and projects the problems of today into the future, backcasting is used in cases where it is desired to actively dictate a future, or where existing trends are leading to an unfavorable state.

In recent years, backcasting has been mostly applied in the futures studies that deal with long-term problems and sustainability solutions (see, e.g., Åkerman 2005; Akerman and Höjer 2006; Höjer, Gullberg and Pettersson 2011; Quist et al. 2011; Vergragt and Quist 2011). The backcasting process in this futures study represents a strategic planning tool for facilitating progress towards achieving the goals of sustainability for those cities that are badging or regenerating themselves as sustainable, or manifestly planning to be or become smart sustainable in the era of big data. Accordingly, it articulates strategic thinking—the why—behind both the vision of the future and the plan for getting there.

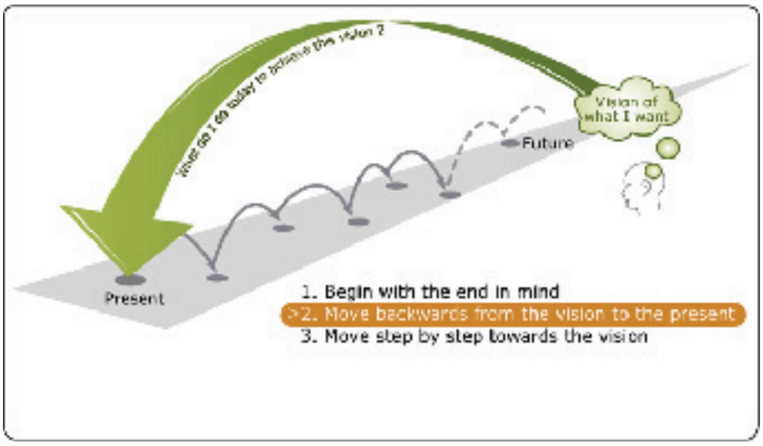

Figure 3.1: The backcasting process from the Natural Step
Source: Holmberg (1998)

3.3.2. Descriptive Case Study

The descriptive case study approach was applied in the four case studies to investigate the prevailing models of sustainable urbanism and the emerging models of smart urbanism (Step 4). The intention of this investigation is to identify the underlying components of the new model of urbanism in terms of its core dimensions, strategies, and solutions, and then to integrate these components into an applied framework for strategic sustainable urban development planning (Step 5). This is in turn intended to inform and guide the strategic planning process of transformative change towards sustainability, which represents the novel model for data-driven smart sustainable cities of the future (Step 6). Overall, by carefully studying any unit of a certain universe, we find out about some general aspects of it, at least a perspective that guides subsequent research. Case studies often represent the first scholarly toe in the water in new research areas.

The case study is a descriptive qualitative methodology that is used as a tool to study specific characteristics of a complex phenomenon. The descriptive case study approach, as defined by Yin (2014, 2017), was identified as the most suitable methodology for the empirical phase of the futures study. This methodology has been chosen considering the nature of the problem being investigated, the research aim, and the present state of knowledge with respect to the topic of data-driven smart sustainable cities. In this context, it involves the description, analysis, and interpretation of the four urban phenomena, with a particular focus on the prevailing conditions pertaining to plans, projects, and achievements. That is, how the selected cities behave as to what has been realized and the ongoing implementation of plans based on the corresponding practices and strategies for sustainable development and technological development. To obtain a detailed form of knowledge in this regard, a five-step process tailored to each of the four case studies was adopted (Table 4.2).

Compact Cities
• Using a narrative framework that focuses on the compact city model and its contribution to the three goals of sustainability as a real–world problem and that provides essential facts about it, including relevant background information • Introducing the reader to key concepts, strategies, practices, and policies relevant to the problem under investigation • Discussing benefits, conflicts, and contentions relevant to the problem under investigation • Explaining the actual solutions in terms of plans, the processes of implementing them, and the expected outcomes. • Offering an analysis and evaluation of the chosen solutions and related issues, including strengths, weaknesses, tradeoffs, and lessons learned.
Eco-Cities
• Using a narrative framework that focuses on the eco-city as a real-world problem and provides essential facts about it, including relevant background information • Introducing the reader to key concepts, models, and design strategies relevant to the problem under investigation • Discussing benefits and research gaps and issues relevant to the problem under investigation • Explaining the actual solutions in terms of plans, the processes of implementing them, and the expected outcomes • Offering an analysis and evaluation of the chosen solutions and related issues, including strengths, weaknesses, tradeoffs, and lessons learned.
Data-Driven Smart Cities

Compact Cities
• Using a narrative framework that focuses on the data-driven smart city as a real–world problem and provides essential facts about it, including relevant background information • Introducing the reader to key concepts, technologies, and data-driven smart sustainable urbanism processes and practices relevant to the problem under investigation • Providing an overview of the literature review previously conducted in relation to the study, which delivers a comprehensive, state–of–the–art review on the sustainability and unsustainability of smart cities in relation to big data technology, analytics, and application in terms of the underlying foundations and assumptions, research problems and debates, opportunities and benefits, technological developments, emerging trends, future practices, and challenges and open issues • Explaining the actual solutions in terms of plans, the processes of implementing them, and the expected outcomes • Offering an analysis and evaluation of the chosen solutions and related issues, including strengths, weaknesses, tradeoffs, and lessons learned.
Environmentally Data-Driven Smart Sustainable Cities
• Using a narrative framework that focuses on data-driven smart solutions and their role and potential in improving and advancing environmental sustainability in the framework of the smart sustainable city as a real–world problem, and provides essential facts about it, including relevant background information. • Introducing the reader to key concepts, core enabling technologies, infrastructures, landscapes, frameworks, as well as urban operating systems and urban operations centers, all with relevance to the problem under study. • Identifying the commonalities and differences between the two cities with respect to the emerging technologies • Explaining the actual solutions in terms of plans and visions, the processes of implementing them, and the realized and expected outcomes • Offering an analysis and evaluation of the relevant solutions and related issues, including strengths, weaknesses, and lessons learned.

Table 3.2. A five-step process tailored to each of the four case studies conducted

The case studies examine contemporary real-world phenomena and seek to inform the theory and practice of data-driven smart sustainable urbanism by illustrating what has worked well, what needs to be improved, and how this can be done. They are particularly useful for understanding how different elements fit together and (co-)produce the observed impacts in a particular urban context based on a set of intertwined factors.

3.3.3. A Pathway-Oriented Category of Backcasting

Developing strategies and pathways to the future has long been the subject of futures studies, especially through the construction of futures visions to achieve the goals of sustainability. Typically, backcasting defines criteria for a desirable future and builds a feasible and logical path between the state of the future and the present. The latter allows to set priorities, develop alternative solutions, and determine the actions that need to be taken. This relates to the backwards-looking analysis step of the backcasting study, which is concerned with developing strategies and pathways to attain the future vision. Determining the strategies and the specific pathways to execute them is the main part of the effort to achieve the overall goal of the future vision by meeting the long-term objectives and targets related to sustainability. At the heart of these strategies and pathways is the practice-oriented process of designing and developing the data-driven smart sustainable city of the future.

Wangel (2011) classifies backcasting into four categories, (1) pathway-oriented backcasting (how to change), (2) target-oriented backcasting (what can change), (3) action-oriented backcasting (who could make change happen), and (4) participation-oriented backcasting (to enhance participation and buy-in by stakeholders). The futures study is concerned with the pathway-oriented category of backcasting (e.g., Bengston Westphal and Dockry 2020; Wangel 2011) where the focus is on how the changes can take place and the measures that support those changes. Here, the setting of strict goals is considered less important (Vergragt and Quist 2011; Wangel 2011) compared to other categories. However, the pathway-oriented category of backcasting in this context entails how to bring different transformations to the multidimensional landscape of the data-driven smart sustainable city of the future, supported with enhanced, new, and innovative institutional practices and competences. usually helps identify critical non-technical triggering measures. All in all, in the quest for the answer to how to reach the future vision, the strategic pathways developed are intended to link goals which may lie far ahead in the future to some decisive steps that are to be designed and taken now to achieve those goals.

3.3.4. The Common Perspectives on Time Horizon in Backcasting

A typical time horizon adopted in many backcasting-oriented futures studies is 50 years. This time horizon is appealing because it is both realistic and far enough away to allow major changes and even disruptions in technologies and cultural norms and values. There also is a large body of work on backcasting that takes the perspective of 25-50 years as a time horizon. The futures study follows this perspective by covering the time period from 2020-2050, the time reasonably needed to achieve the status of the data-driven smart sustainable city of the future as a desired vision. The rationale for pursuing this is that this model of urbanism concerns particularly—but not only—those cities that are badging or regenerating themselves as sustainable, or manifestly planning to be or become smart sustainable in the era of big data. As they move towards 2050, a number of concrete actions will be taken along the way to make the actual progress towards achieving the goals of sustainability—with the support of emerging and future ICT. And what this entails in terms of developing the IoT and big data technologies and implementing their novel applications in the operational management and development planning of sustainable cities, as well as enchanting existing, creating new, and establishing innovative technical and institutional competences on a citywide scale.

It is worth noting that the futures study is not setting out a fixed timeframe as the future is unknown and the world is uncertain. It follows that it may take longer for sustainable cities to get closer to or reach the final destination. Not to mention those cities that are just embarking on the journey of regenerating themselves as sustainable, or that are manifestly planning to be or become such. Otherwise, it would principally depend on the level of the actual progress a given sustainable city has made in the different areas of sustainability, as well as on the degree of its readiness to introduce data-driven technology in its management together with the degree of the implementation of applied data-driven solutions developed for its management. Regardless, the time horizon of 25-50 years associated with the future vision is a basic principle to allow the policy and planning actions to make the transition to the data-driven smart sustainable city of the future.

4. Research Contributions

The main focus of this research is on the uses of the IoT and big data technologies and their novel applications offered by smart cities in monitoring, understanding, analyzing, planning, and managing sustainable cities so as to improve, advance, and maintain their contribution to the goals of sustainability. This was accomplished by clarifying a future urban model and working towards achieving that goal. This planning process of backcasting represents a strategic roadmap to transformational change for sustainability. In this thesis, the futures study sets out to analyze, investigate, and develop a novel model for data-driven smart sustainable cities of the future. This futures research has resulted in the following contributions, each is presented based on the published title, authors, and publication details, followed by the abstract, the relevance to the thesis, a detailed description of the work, and the author's contribution.

4.1. Contribution 1

P1: Bibri, Simon Elias and Krogstie, John: **"Smart Sustainable Cities of the Future: An Extensive Interdisciplinary Literature Review".** Sustainable Cities and Society 2017; Volume (31) pp.183-212

Abstract:

In recent years, the concept of smart sustainable cities has come to the fore. And it is rapidly gaining momentum and worldwide attention as a promising response to the challenges of sustainability. This paper provides a comprehensive overview of the field of smart sustainable cities in terms of its underlying foundations and assumptions, state–of–the art research, research opportunities and horizons, emerging scientific and technological trends, and future planning practices. As to the design strategy, the paper reviews the existing models of sustainable cities and smart cities. Their strengths and weaknesses are discussed with particular emphasis being placed on the extent to which sustainable cities contribute to the goals of sustainable development and whether smart cities incorporate these goals. To identify the related challenges, those models are evaluated and compared in line with the vision of sustainability. The research gaps within the field of smart sustainable cities are identified in accordance with and beyond the research being proposed. As a result, an integrated approach is proposed based on an applied theoretical perspective to align the existing problems and solutions identification for future practices in the area of smart sustainable urbanism. As to the findings, this paper shows that critical issues remain unsettled, less explored, largely ignored, or theoretically underdeveloped for applied purposes with respect to the existing models of sustainable urban form as to their contribution to sustainability, among other things. It also reveals that numerous research opportunities are available and can be realized in the realm of smart sustainable cities. In this regard, our perspective on the topic is to develop a theoretically and practically convincing model of smart sustainable cities and a framework for strategic smart sustainable urban development planning. This is to address the key limitations, paradoxes, uncertainties, and fallacies pertaining to the existing models of sustainable urban form—with the support of advanced ICT, notably big data technologies and their advanced applications. We conclude that the applied theoretical inquiry into smart sustainable cities of the future is deemed of high pertinence and importance—given that the research in the field is still in the early stages of its development, and that the subject matter draws upon contemporary and influential theories with practical applications. This comprehensive overview of and critique on existing work on smart sustainable cities provide a valuable and seminal reference for researchers and practitioners in related research communities and the necessary material to inform these communities of the latest developments in the area of smart sustainable urbanism. In addition, the proposed approach is believed to be the first of its kind. That is, it has not been, to the best of our knowledge, investigated or produced elsewhere.

Relevance to the Thesis: P1 gives insights into the state-of-the-art research in sustainable cities and smart cities as the two main research areas of the PhD study, as well as their integration. It provides a foundation for the PhD study in terms of what is already known, produces a rationale for the PhD study as to its contribution of something new to the body of knowledge, helps understand where excess research exists and what kind of questions are left unanswered, and accordingly substantiates the presence of the research problem in regard to what should be known. In particular, this paper states the research problems and their potential solutions, showing how the knowledge gaps can be filled within the field of sustainable cities. It also justifies the further investigation of sustainable cities in terms of compact cities and eco-cities to find out whether any progress has been recently made towards urban sustainability (P6 and P7). This is intended to inform the development of the new model of urbanism proposed by this review paper. This paper contributes to answering RQ1 and produces C1.

Description of the work:

P1 provides an extensive literature review of the fields of sustainable cities and smart cities, analyzing and evaluating the existing knowledge within the emerging interdisciplinary field of smart sustainable cities. It describes and discusses a number of concepts, theories, and discourses; identifies many research issues and opportunities; and sheds light on emerging scientific and technological trends and future planning practices. Of more relevance to the topic of the PhD study, P1 identifies the problems, issues, and challenges associated with sustainable cities and smart cities by evaluating and comparing them in the context of sustainability. Accordingly, it highlights a number of research gaps, mostly questions that have not been answered (appropriately or at all) by any of the existing research within the field of sustainable cities in terms of their contribution to sustainability, as well as within the emerging field of smart sustainable cities. This gap analysis focuses on the difference between what is known and what should be known, thereby identifying what is missing in the literature, particularly in regard to the relationship between sustainable cities and smart cities. Worth pointing out, moreover, is that the new idea of smart sustainable cities represents a gap in itself as it is still evolving as a paradigm of urbanism. It follows that this idea has not been studied from the perspective of combining and integrating the design strategies and environmental technology solutions of sustainable cities and the data-driven technologies and solutions of smart cities.

P1 provides the basis of the PhD research as to its smart sustainable strand. It was revealed that numerous research opportunities are available and can be realized in the realm of smart sustainable cities. This integrated model of urbanism was proposed to align the existing problems and solutions identified for future practices within sustainable urban development. Its primary objective is to address and overcome the key issues, problems, and challenges associated with the existing models of sustainable cities—compact cities and eco-cities, with the support of what smart cities have to offer in regard to advanced ICT, notably big data technologies. This paper concluded that the applied theoretical inquiry is of high pertinence and importance—given that the research within the field of smart sustainable cities is still in the early stages of its development, and that the subject area draws upon influential and contemporary theories from a number of city-related disciplines that have high integration, fusion, and application potential.

Author's Contribution:

This paper was entirely written by Simon Elias Bibri. John Krogstie provided comments and suggestions for improvements prior to the review process.

4.2. Contribution 2

P2: Bibri, Simon Elias: **"On the Sustainability of Smart and Smarter Cities and Related Big Data Applications: An Interdisciplinary and Transdisciplinary Review and Synthesis"**. Journal of Big Data 2019; Volume 6.(25) pp. 1-64

Abstract:

There has recently been a conscious push for cities across the globe to be smart and even smarter and thus more sustainable by developing and implementing big data technologies and their applications across various urban domains in the hopes of reaching the required level of sustainability and improving the living standard of citizens. Having gained momentum and traction as a promising response to the transition towards sustainability and to the challenges of urbanization, smart and smarter cities are increasingly adopting the advanced forms of ICT to improve their performance with regard to sustainable development urban growth. One of such forms that has tremendous potential to enhance urban operations, functions, services, designs, strategies, and policies in this direction is big data technologies and their applications. However, topical studies on data-driven applications in the context of smart and smarter cities tend to deal largely with economic growth and the quality of life in terms of service efficiency and betterment, while overlooking and barely exploring the untapped potential of such applications for advancing sustainability. In fact, smart and smarter cities raise several issues and involve significant challenges when it comes to their development and implementation in the context of sustainability. This paper provides a comprehensive, state-of-the-art review and synthesis of the field of smart and smarter cities in regard to sustainability and related big data technologies and their applications in terms of the underlying foundations and assumptions, research issues and debates, opportunities and benefits, technological developments, emerging trends, future practices, and challenges and open issues. This study shows that smart and smarter cities are associated with misunderstanding and deficiencies as regards their incorporation of and contribution to sustainability, respectively. Nevertheless, as also revealed by this study, tremendous opportunities are available for utilizing data-driven applications in smart cities of the future to improve their contribution to sustainability through optimizing and enhancing urban operations, functions, services, designs, strategies, and policies, as well as finding answers to challenging analytical questions and advancing knowledge forms. However, just as there are immense opportunities ahead to embrace and exploit, there are enormous challenges ahead to address and overcome in order to achieve a successful implementation of data-driven technologies and solutions in smart cities of the future.

Relevance to the Thesis: P2 expands on P1 with respect to the second main research area of the PhD study. In so doing, it presents the current status of the body of knowledge in the field of smart cities of the future from a sustainability perspective. This helps to understand the feasible solutions for the problems, issues, and challenges related to sustainable cities (P1) by highlighting the potentials and opportunities of data-driven technologies for advancing sustainability within smart cities of the future. The identified data-driven technology solutions are intended to be applied in the operational management and development planning of sustainable cities in order to improve and advance their contribution to the goals of sustainability. In addition, this paper presents the relevant research issues associated with smart cities of the future and the challenges they are facing in relation to the use and application of data-driven technologies. In relation to the former, this paper justifies the further investigation of smart cities to find out the extent to which they incorporate the goals of sustainability in their development strategics, as well as which of these goals they tend to prioritize. Concerning the latter, it is implied that sustainable cities are also concerned with and need to address and overcome the same challenges in order to successfully implement data-driven technology solutions so as to optimize, enhance, and maintain their performance with respect to their contribution to sustainability. This paper contributes to addressing RQ1 and leads to C2.

Description of the work:

P2 provides a comprehensive state-of-the-art review and synthesis of the field of smart cities of the future in the context of sustainability and related big data technologies and their novel applications. By the same token, P2 describes and discusses a number of concepts, theories, and discourses; identifies many research issues and opportunities; highlights the benefits and potentials of applied technology solutions; shed lights on emerging technological trends and future planning practices; and examines the key challenges and open issues associated with the uses of big data analytics. Of particular relevance to the topic of the PhD study is the potentials and benefits of data-driven technologies and solutions for tackling the problems of sustainability and urbanization, as well as the challenges and open issues associated with their uses, in the context of smart cities of the future. In addition, P2 identifies many research gaps within the field of smart cities of the future, particularly in relation to their contribution to sustainability.

P2 also provides the basis of the PhD research, particularly in relation to its smart strand. It was revealed that tremendous opportunities are available for developing and implementing data-driven applications within smart cities of the future to improve their contribution to the goals of sustainability. The primary intention is to corroborate the strengths of smart cities of the future that sustainable cities need to embrace and adopt so as to optimize and enhance their operations, functions, services, designs, strategies, and policies in line with the vision of sustainability, This is justified by the kind of well-informed decisions enabled by the deep insights that can be extracted by the process of big data analytics in the form of applied intelligence, adding to the ability of this process to find answers to challenging analytical questions and thus advancing knowledge forms. It was also shown that enormous challenges and open issues need to be addressed and overcome to achieve a successful implementation of data-driven applications in the ambit of smart cities of the future. The primary intention is to point to the fact that sustainable cities are also concerned with the same challenges and open issues as to finding ways to solve them in order to be able to optimize, enhance, and maintain their performance with respect to their contribution to sustainability. The main facet of this comprehensive literature study that the PhD study is concerned with is the untapped potential of big data technologies for advancing sustainable cities.

Author's Contribution:

This paper was entirely written by Simon Elias Bibri.

4.3. Contribution 3

P3: Bibri, Simon Elias and Krogstie, John: **"A Scholarly Backcasting Approach to a Novel model for Smart Sustainable Cities of the Future: Strategic Problem Orientation".** Journal of Futures Studies 2019; Volume 6.(3) pp. 1-27

Abstract:

Sustainable cities have, since the early 1990s, been the leading global paradigm of urbanism thanks to the different models of sustainable urban form proposed as new frameworks for redesigning and restructuring urban places to achieve sustainability. Indeed, huge advances in some areas of sustainability knowledge and a multitude of exemplary practical initiatives have been realized, thereby raising the profile of sustainable cities worldwide. The change is still inspiring and the challenge continues to induce scholars and practitioners to enhance existing and propose new models. Especially, sustainable urban forms have been problematic, whether in practice or discourse, so has yet knowing to what extent any progress has been made towards sustainable cities. They are associated with a number of problems, issues, and challenges and thus much more needs to be done considering the very fragmented and conflicting picture that arises of change on the ground in the face of the expanding urbanization. This involves the question of how they should be monitored, understood, analyzed, planned, and even integrated so as to improve and advance their contribution to sustainability. This brings us to the issue of sustainable cities and smart cities being extremely fragmented as landscapes and weakly connected as approaches, despite the proven role and untapped potential of advanced ICT, especially big data technologies and their novel applications, for advancing sustainability under what is labeled 'data-driven smart sustainable cities.' Essentially, there are multiple visions of and pathways to achieving data-driven smart sustainable cities based on how they can be

conceptualized and operationalized. This paper details the two parts of strategic problem orientation by answering the guiding questions for Steps 1 and 2 of the futures study being conducted. This study aims to analyze, investigate, and develop a novel model for smart sustainable cities of the future using backcasting as a scholarly approach. It involves a series of papers of which this paper is the first one. We argue that a deeper understanding of the multi-faceted processes of change or the interplay between social, technological, and scientific solutions is required to achieve more sustainable cities. Visionary images of a long-term future can stimulate an accelerated movement towards achieving the long-term goals of sustainability. The proposed model is believed to be the first of its kind and thus has not been, to the best of one's knowledge, produced, nor is it being currently investigated, elsewhere.

Relevance to the Thesis: P3 details the strategic problem orientation of the futures study in terms of the current situation and the dominating trends and expected developments related to the future model of urbanism to be investigated and developed. As regards the current situation, it focuses on the problems, issues, and challenges pertaining to sustainable cities addressed by the PhD study, unlike P1 and P2 which provide a state-of-the-art review from a broader perspective. Additionally, it outlines the long-term objectives and targets related to sustainability. These are to be refined based on the outcomes of the four case studies to be conducted. Furthermore, it provides the evaluation for grounding the future vision to be constructed in realism, thereby underpinning the normative side of backcasting. This paper addresses RQ1 and results in C3. It represents the Steps 1 and 2 of the futures study.

Description of the work:

P3 initiates the futures study by addressing its strategic problem orientation phase, which consists of two parts. In Part 1, this paper specifies the aim, objectives, and purpose of the futures study itself. In Part 2, it describes and analyzes the dominating trends and identifies the expected developments related to the future model of urbanism, as well as clarifies the current situation. With respect to the latter, it establishes the link between the problems, issues, and challenges pertaining to sustainable cities and the potential solutions offered by smart cities of the future on the basis of the IoT and big data technologies. Additionally, it outlines the long-tern objectives and targets related to sustainability with respect to the future model of urbanism to be investigated. The objectives are translated into specific targets, and then both are used to generate the future vision. These objectives and targets are to be refined based on the new theoretical and practical knowledge to be gained from carrying out the four case studies representing the empirical phase of the futures study. The main outcome of this paper was foundational for the backcasting study and preparatory as to the backcasting process, setting the futures research in proper perspective

Author's Contribution:

This paper was entirely written by Simon Elias Bibri. John Krogstie provided comments and suggestions for improvements prior to the review process.

4.4. Contribution 4

P4: Bibri, Simon Elias and Krogstie, John: **"Generating a Vision for Smart Sustainable Cities of the Future: A Scholarly Backcasting Approach"**, European Journal of Futures Research; Volume 7.(5) pp. 1-20

Abstract:

Sustainable cities have been the leading global paradigm of urbanism. Undoubtedly, sustainable development has, since its widespread diffusion in the early 1990s, positively influenced city planning and development. This pertains to the immense opportunities that have been explored and the enormous benefits that have been realized in relation to sustainable urban forms, especially compact cities and eco-cities. However, sustainable *cities are still associated with a number of problems, issues, and challenges. This mainly involves the question of how they should be monitored, understood, analyzed, and planned to improve and advance their contribution to sustainability. This in turn brings us to the current issue related to the weak connection between and the extreme fragmentation of sustainable cities and smart cities as approaches and landscapes, respectively, despite the proven role of advanced ICT, coupled with the untapped potential of big data technologies and their novel applications, in supporting sustainable cities in enhancing and optimizing their performance under what is labeled "data-driven smart sustainable cities." Meanwhile, we are in the midst of an expansion of time horizons in city planning and development. In this context, sustainable cities across the globe have adopted ambitious smart goals that extend far into the future. Essentially, there are multiple visions of and pathways to achieving data-driven smart sustainable cities based on how they can be conceptualized and operationalized. The aim of this paper is to generate a vision for data-driven smart sustainable cities of the future by answering the six guiding questions for Step 3 of the futures study being conducted. This futures study aims to analyze, investigate, and develop a novel model for data-driven smart sustainable cities of the future using backcasting as a scholarly and planning approach. It involves a series of papers of which this paper is the second one, following the earlier paper with Steps 1 and 2. Visionary images of a long-term future can stimulate an accelerated movement towards achieving the long-term goals of sustainability. The proposed model is believed to be the first of its kind and thus has not been, to the best of one's knowledge, produced, nor is it being currently investigated, elsewhere.*

Relevance to the Thesis: Reaching the goals of urban sustainability is an unlikely outcome of any effort deployed for advancing sustainable cities without first defining a future place where to land. In this light, P4 generates a vision for a sustainable future to be attained based on the outcome of P3, and addresses several related issues in relevance to Step 3 of the futures study. At the core of this vision is the integration of sustainable cities and smart cities on the basis of big data technologies—in short, data-driven smart sustainable cities of the future. This paper highlights the prevailing tendency to direct the recent advances in ICT towards addressing and overcoming the mounting challenges of sustainability in the light of the escalating trend of urbanization. Overall, it initiates the backcasting process by envisioning and analyzing the state of the future and thus clarifying the new model of urbanism to be investigated (P5, P6, P7, P8, and P9). This paper answers RQ2 and produces C4. It represents the Step 3 of the futures study.

Description of the work:

P4 defines and describes a vision for a sustainable future in which the problems, issues, and challenges related to sustainable cities have been solved by means of the data-driven technologies and solutions offered by smart cities of the future. This in turn means meeting the long-term objectives and targets specified in P3. Additionally, however, this paper addresses several questions involving the requirements of the future vision, how the future vision is different from the current model of urbanism, the rationale for developing the future vision, and which technologies have been used in the future vision. The future vision was generated based on the assessment of the current situation as well as the analysis of the dominating trends and expected developments related to the future model of urbanism (P3). Thus, a prior evaluation grounded the vision in realism by putting the current circumstances and capabilities at the center of attention. In a sense, the future vision revolves around a co-evolution process of sustainability and technology within the domain of urbanism —shaped by the idea of combining and integrating the prevailing paradigms of sustainable urbanism and the emerging paradigms of smart urbanism in terms of their dimensions, strategies, and solutions. The generated future vision was refined and made concise while maintaining its core components in light of the new theoretical and practical knowledge gained from conducting the case study research. Furthermore, constructing and refining the future vision (P4 and P10) entails retaining the best of what we already have that have been successfully enacted in real-world cities, making use of the things that have been demonstrably better in the past, while being selective in adopting the best of what is emerging and promising, making use of the things that will add a whole new dimension to sustainability in terms of harnessing its synergistic effects, balancing its dimensions, and thus boosting its benefits.

Author's Contribution:

This paper was entirely written by Simon Elias Bibri. John Krogstie provided comments and suggestions for improvements prior to the review process.

4.5. Contribution 5

P5: Bibri, Simon Elias: **"A Methodological Framework for Futures Studies: Integrating Normative Backcasting Approaches and Descriptive Case Study Design for Strategic Data-Driven Smart Sustainable City Planning**". Energy Informatics 2020; Volume 3.(31) pp. 1-42

Abstract:

Originally proposed as an alternative to traditional energy planning methodology in the 1970s, backcasting is increasingly applied in futures studies related to sustainability, as it is viewed as a natural step in operationalizing sustainable development. This futures study is concerned with data-driven smart sustainable urbanism as an instance of sustainable urban development—a strategic approach to achieving the long-term goals of urban sustainability. This is at the core of backcasting, which typically defines criteria for a desirable (sustainable) future and builds a set of feasible and logical pathways between the state of the future and the present. This paper reviews, discusses, and justifies the methodological framework applied in the futures study. This aims to analyze, investigate, and develop a novel model for data-driven smart sustainable cities of the future as a form of transformative change towards sustainability. This paper corroborates that the backcasting approach—as applied in the futures study—is well-suited for long-term urban problems and sustainability solutions due to its normative, goal-oriented, and problem-solving character. It also suggests that case study research is the most effective way to underpin and increase the feasibility of future visions. Indeed, the case study approach as a research strategy facilitates the investigation and understanding of the real-world phenomena involved in the construction of the future vision in the backcasting study. The novelty of this work lies in the integration of a set of the underlying principles of several normative backcasting approaches with descriptive case study design to devise a framework for strategic data-driven smart sustainable city planning whose core objective is clarifying which city model is desired and working towards that goal. Visionary images of a long-term future based on normative backcasting can spur innovative thinking about and accelerate the movement towards sustainability. The proposed framework serves to help researchers in analyzing, investigating, and developing future models of sustainable urbanism, smart urbanism, and smart sustainable urbanism, as well as to support policymakers and facilitate and guide their actions as to transformative changes towards sustainability based on empirical research.

Relevance to the Thesis: P5 focuses on the methodological framework applied in the futures study, which combines normative backcasting and descriptive case study as qualitative approaches. The backcasting approach was employed to achieve the overall aim of the futures study. The case study approach, which concerns the empirical phase of the futures study, was adopted to examine and compare two of a total of six cases in each of the four case studies conducted on compact cities, eco-cities, data–driven smart cities, and environmentally data-driven smart sustainable cities. The methodological framework explores the topic of data-driven smart sustainable cities of the future, a novel model of urbanism that integrates these four models of urbanism. This paper contributes partially to answering RQ3 and partially to producing C5. This paper constitutes part of the Step 4 of the futures study.

Description of the work:

P5 reviews, discusses, and justifies the methodological framework applied in the futures study. The framework combines and integrates a set of principles underlying several normative backcasting approaches as well as descriptive case study design. Employing the latter as part of backcasting stems from the motivation to illuminate the four complex urban phenomena underpinning the backcasting of the future phenomenon of data-driven smart sustainable cities. That is, the strategic planning process of transformative change towards sustainability. To backcast in this futures research is about combining and integrating the dimensions, strategies, and solutions of sustainable cities and smart cities into a new model of urbanism based on the outcome of the case study research together with creative and visionary ideas.

It was corroborated that the backcasting approach—as applied in the futures study—is well-suited for long-term urban problems and urban sustainability solutions due to its normative, goal-oriented, and problem-solving character. The problems and solutions relevant to the futures study were identified in P1 and P2 and summarized in P3. It was suggested that case study research is the most effective way to underpin and increase the feasibility of the future vision due to its ability to facilitate the investigation and understanding of the underlying principles in the real-world urban phenomena involved in the construction of the future vision. Worth pointing out is that the intention of writing this paper after conducting the four case studies is to compile and enhance the knowledge about the research approaches tailored to different context for the purpose of devising a methodological framework for data-data-driven smart sustainable city planning. This is in turn to assist researchers in analyzing, investigating, and developing future models of smart sustainable urbanism, as well as in supporting policymakers and facilitating and guiding their actions as to transformative changes towards sustainability based on empirical research.

Author's Contribution:

This paper was entirely written by Simon Elias Bibri.

The approach of the futures study to empirical research involves four case studies. Each of which examines and compares two of a total of six cases from the ecologically and technologically leading cities in Europe. This investigation is done within the frameworks of compact cities, eco-cities, data–driven smart cities, and environmentally data-driven smart sustainable cities, and thus involves four papers (P6, P7, P8, and P9).

Relevance to the Thesis: P6, P7, P8, and P9 illuminate the urban phenomena of compact urbanism, ecological urbanism, data–driven smart urbanism, and environmentally data-driven smart sustainable urbanism. The outcome of this work has a threefold purpose. Firstly, it provides the foundational elements of the framework for strategic sustainable urban development planning that is to be developed by means of P10. Secondly, it refines the vision of the future (P10) and thus the broadly defined objectives and targets it is translated to (P11) in the light of the new insights gained from the case study research conducted. Thirdly, it underpins and informs the development of the novel model for data-driven smart sustainable cities of the future (P11, P12, and P13). These four papers, combined, contribute to answering RQ4, RQ5, and RQ6 and to generating C6 and C7. They represent together with P5 the Step 4 of the futures study.

P6: **Bibri, Simon Elias,** Krogstie, John and Kärrholm, Mattias: **"Compact City Planning and Development: Emerging Practices and Strategies for Achieving the Goals of Sustainability"**. Developments in the built environment 2020; Volume 4 pp. 1-20

Abstract:

The compact city is one of the leading paradigms of sustainable urbanism. Compact city planning and development has, over the last 30 years or so, been the preferred response to the challenges of sustainable development. It is strongly promoted by global and local policies due to its positive outcomes in terms of contributing to the three goals of sustainability. This paper examines how the compact city model is practiced and justified in urban planning and development with respect to the three dimensions of sustainability, and whether any progress has been made in this regard. To illuminate this urban phenomenon accordingly, a *descriptive case study is adopted as a qualitative methodology where the empirical basis is mainly formed by the official plans and documents of two Swedish cities: Gothenburg and Helsingborg, in combination with qualitative interview data and secondary data. This study shows that compactness, density, diversity, mixed land use, sustainable transportation, and green space are the core design strategies of compact city planning and development, with the latter being contextually linked to the concept of green structure, an institutional setup under which the two cities operate. Moreover, at the core of the compact city model is the clear synergy between the underlying strategies in terms of their cooperation to produce combined effects greater than the sum of their separate effects with respect to the benefits of sustainability as to its tripartite composition. Further, this study demonstrates that the compact city model as practiced by the two cities is justified by its ability to contribute to the economic, environmental, and social goals of sustainability. However, the economic goals dominate over the environmental and social goals, notwithstanding the claim about the three dimensions of sustainability being equally important at the discursive level. Nevertheless, new measures are being developed and implemented to strengthen their influence over urban planning and development practices towards balancing the three goals of sustainability.*

Description of the work:

P6 investigates how the compact city model is practiced and justified in urban planning and development with respect to the three dimensions of sustainability, and whether any progress has been made in this regard. Specifically, it focuses on the prevalent design strategies of the compact city model, the ways in which they mutually complement and beneficially affect one another in terms of producing the expected benefits of sustainability, as well as the extent to which the compact city model supports the balancing of the three goals of sustainability.

It was demonstrated that compactness, density, diversity, mixed land use, sustainable transportation, and green space are the core design strategies of compact city planning and development, with the latter being contextually linked to the concept of green structure, an institutional setup under which the two investigated cities operate. Also revealed was a clear synergy between the underlying design strategies in terms of their cooperation to produce combined effects greater than the sum of their separate effects with respect to the benefits of sustainability as to its tripartite composition. Moreover, P6 showed that the compact city model as practiced by the two cities is justified by its ability to contribute to the economic, environmental, and social goals of sustainability. However, it indicated that the environmental and social goals still play second fiddle, and that new measures are being implemented to strengthen the influence of these goals in urban planning and development practices. In this context, it was particularly noticeable that compact urbanism is being enhanced with some elements of ecological urbanism and strengthened by new institutionalised practices accordingly to support the balancing of the three dimensions of sustainability.

P7: Bibri, Simon Elias and Krogstie, John: **"Smart Eco–City Strategies and Solutions: The Cases of Royal Seaport, Stockholm, and Western Harbor, Malmö, Sweden"**. Urban Science 2020; Volume 4.(1) pp. 1-42

Abstract:

Sustainable urbanism is seen today as one of the keys towards unlocking the quest for a sustainable society. As a central paradigm of sustainable urbanism, the eco-city is promoted by global and local policies as one of the preferred responses to the challenges of sustainable development. It is argued that eco-city strategies are expected to deliver positive outcomes in terms of providing healthy and livable human environments in conjunction with minimal demand on resources and thus minimal environmental impacts. As such, it is pertinent to examine how the eco-city model and especially its three sustainability dimensions is practiced and justified in urban planning and development at the local level. This is motivated by the increased interest in developing sustainable urban districts. In this light, this paper seeks to answer these two questions: What *are the key strategies of the eco-city district model, and in what ways do they mutually complement one another in terms of producing the expected tripartite value of sustainability? To what extent does the eco-city district model support and contribute to the environmental, economic, and social goals of sustainability? To illuminate the phenomenon of the eco-city district accordingly, a descriptive case study is adopted as a qualitative research methodology, where the empirical basis is mainly formed by urban planning and development documents in two eco-city districts—Royal Seaport, Stockholm, and Western Harbor, Malmö, Sweden—in combination with qualitative interview data and secondary data. This study shows that the eco-city district models of SRS and Western Harbor involve mainly design and technology, supported with behavioral change, as key strategies and solutions for achieving urban sustainability. Design encompasses greening, passive solar houses, sustainable transportation, mixed land use, and diversity. And technology comprises green technologies, energy efficiency technologies, and waste management systems. Design contributes to the three goals of sustainability, and technology contributes mostly to the environmental and economic goals of sustainability. Behavioral change is associated with sustainable travel, waste separation, and energy consumption. Moreover, at the core of the eco-city district model is the clear synergy between the underlying strategies in terms of their cooperation to produce combined effects greater than the sum of their separate effects with respect to the benefits of sustainability. Further, this study demonstrates that while the environmental, economic, and social goals of sustainability are represented in eco-city district strategies on a discursive level, institutionalized planning practices show that the environmental goals remain at the core of planning, while the economic and social goals still play second fiddle. Nevertheless, new measures have recently been implemented in Western Harbor that are expected to strengthen their influence over urban development practices, whereas the Royal Seaport program mainly focuses on the environmental and some economic aspects, which is a shortcoming that should be recognized and dealt with.*

Description of the work:

P7 investigates how the eco-city model, especially its three sustainability dimensions, is practiced and justified in urban planning and development at the local level. Specifically, it focuses on the core strategies and solutions of the eco-city district model, the way in which they mutually complement one another in terms of producing the expected benefits of sustainability, as well as the extent to which the eco-city district model supports the integration of the three goals of sustainability.

It was shown that the eco-city district model involves mainly design and technology as the core strategies and solutions for achieving urban sustainability. Moreover, at the core of the eco-city district model is the clear synergy between the core underlying strategies and solutions in terms of their cooperation to produce combined effects greater than the sum of their separate effects with respect to the benefits of sustainability, yet with its environmental dimension clearly dominating over its economic and social dimensions. This is due to the fact that the eco-city emphasizes ecological design, ecological diversity, and passive solar design, as well as environmental management and other key environmentally sound policies. Thus, the environmental goals remain at the core of planning, while the economic and social goals still play second fiddle in ecological urbanism. Nevertheless, it was observed that new measures are being implemented to strengthen the influence of these goals over urban planning and development practices, but only in one of the two investigated cases. Regardless, the social goals remain of less focus compared to the economic goals.

P8: Bibri, Simon Elias and Krogstie, John: **"The emerging Data–driven Smart City and its Innovative Applied Solutions for Sustainability: The cases of London and Barcelona".** Journal of Energy Informatics 2020; Volume (3).5 pp. 1-42

Abstract:

The big data revolution is heralding an era where instrumentation, datafication, and computation are increasingly pervading the very fabric of cities. Big data technologies have become essential to the *functioning of cities. Consequently, urban processes and practices are becoming highly responsive to a form of data-driven urbanism that is the key mode of production for smart cities. Such form is increasingly being directed towards tackling the challenges of sustainability in the light of the escalating urbanization trend. This paper investigates how the emerging data-driven smart city is being practiced and justified in terms of the development and implementation of its innovative applied solutions for sustainability. To illuminate this new urban phenomenon, a descriptive case study is adopted as a qualitative research methodology to examine and compare London and Barcelona as the leading data-driven smart cities in Europe. This study shows that these cities have a high level of the development of applied data-driven technologies, but they slightly differ in the level of their implementation in different city systems and domains in relation to the various areas of sustainability. They also moderately differ in the degree of their readiness as to the availability and development level of the competences and infrastructure needed to generate, transmit, process, and analyze large masses of data to extract useful knowledge for enhanced decision making and deep insights pertaining to urban operational functioning, management, and planning in relation to sustainability. London takes the lead as regards the ICT infrastructure and data sources, whereas Barcelona has the best practices in the data-oriented competences, notably horizontal information platforms, operations centers, dashboards, training programs and educational institutes, innovation labs, research centers, and strategic planning offices. This research enhances the scholarly community's current understanding of the new phenomenon of the data-driven city with respect to the untapped synergistic potential of the integration of smart urbanism and sustainable urbanism for advancing sustainability in the light of the emerging paradigm of big data computing. No previous work has, to the best of our knowledge, explored and highlighted the link between the data-driven smart solutions and the sustainable development strategies in the context of data-driven sustainable smart cities as an emerging paradigm of urbanism.*

Description of the work:

P8 investigates how the emerging data-driven smart city is practiced and justified in terms of the development and implementation of its innovative technologies and solutions for sustainability. It was shown that this emerging paradigm of urbanism has a high level of the development of applied data-driven technologies as well as their implementation in different urban systems to optimize and enhance their performance in relation to the different aspects of sustainability. The high level of the development of data-driven technologies (notably ICT infrastructure and data sources) is associated with the degree of the readiness of the city administration to introduce data-driven technologies in operational management and development planning. The high level of the implementation of data-driven technologies is associated with the degree of the adoption of applied data-driven solutions in the different spheres of the city administration, including transport, traffic, energy, environment, citizen participation, public safety, and healthcare. In this respect, a number of technical and institutional competences are employed and established to improve the different areas of sustainability, notably horizontal information platforms, operations centers, dashboards, educational institutes and training programs, innovation labs, research centers, and strategic planning and policy offices. The outcome of this paper demonstrates the untapped synergistic potential of the integration of innovative solutions and sustainable strategies on the basis of the IoT and big data analytics.

P9: Bibri, Simon Elias and Krogstie, John: **"Environmentally Data-driven Smart Sustainable Cities: Applied innovative Solutions for Energy Efficiency, Pollution Reduction, and Urban Metabolism"** Energy Informatics 2020; Volume (3).29 pp. 1-59

Abstract:

The IoT and big data technologies have become essential to the functioning of both smart cities and sustainable cities, and thus, urban operational functioning and planning are becoming highly responsive to a form of data-driven urbanism. This offers the prospect of building models of smart sustainable cities functioning in real time from routinely sensed data. This in turn allows to monitor, understand, analyze, and

plan such cities to improve their energy efficiency and environmental health in real time thanks to new urban intelligence functions as an advanced form of decision support. However, prior studies tend to deal largely with data-driven technologies and solutions in the realm of smart cities, mostly in relation to economic and social aspects, leaving important questions involving the underlying substantive and synergistic effects on environmental sustainability barely explored to date. These issues also apply to sustainable cities, especially eco-cities. Therefore, this paper investigates the potential and role of data-driven smart solutions in improving and advancing environmental sustainability in the context of smart cities as well as sustainable cities, under what can be labeled "environmentally data-driven smart sustainable cities." To illuminate this emerging urban phenomenon, a descriptive case study is adopted as a qualitative research methodology§ to examine and compare Stockholm and Barcelona as the ecologically and technologically leading cities in Europe, respectively. The results show that smart grids, smart meters, smart buildings, smart environmental monitoring, and smart urban metabolism are the main data-driven solutions applied for improving and advancing environmental sustainability in both eco-cities and smart cities. There is a clear synergy between such solutions in terms of their interaction or cooperation to produce combined effects greater than the sum of their separate effects—with respect to the environment. This involves energy efficiency improvement, environmental pollution reduction, renewable energy adoption, and real-time feedback on energy flows, with high temporal and spatial resolutions. Stockholm takes the lead over Barcelona as regards the best practices for environmental sustainability given its long history of environmental work, strong environmental policy, progressive environmental performance, high environmental standards, and ambitious goals. It also has, like Barcelona, a high level of the implementation of applied data-driven technology solutions in the areas of energy and environment. However, the two cities differ in the nature of such implementation. We conclude that city governments do not have a unified agenda as a form of strategic planning, and data-driven decisions are unique to each city, so are environmental challenges. Big data are the answer, but each city sets its own questions based on what characterize it in terms of visions, policies, strategies, pathways, and priorities.

Description of the work:

P9 investigates the potential and role of data-driven smart solutions in improving and advancing environmental sustainability in the context of smart cities as well as sustainable cities, under what can be labeled "environmentally data-driven smart sustainable cities." P9 also provides an overview of the technical literature on the IoT and big data technologies within the framework of smart sustainable cities. It was shown that smart grids, smart meters, smart buildings, smart environmental monitoring, and smart urban metabolism are the main data-driven solutions applied for improving and advancing environmental sustainability in eco-cities and smart cities combined. There is a clear synergy between such solutions in terms of their cooperation to produce combined effects greater than the sum of their separate effects—with regard to the environment. It was concluded that city governments do not have a unified agenda as a form of strategic planning, and data-driven decisions are unique to each city, so are environmental challenges. Big data are the answer, but each city sets its own questions based on what characterize it in terms of visions, policies, strategies, pathways, goals, and priorities. The main intention of examining and comparing the two emerging paradigms of smart urbanism (data-driven cities) and sustainable urbanism (eco-cities) under "environmentally data-driven smart sustainable cities" is to combine what they have as strengths, harness their clear synergies, and to offer an opportunity for both cities to learn from each other in the area of environmental sustainability and technology. This is also of strategic value in terms of increasing the feasibility of the future vision.

The rationale for conducting the fourth case study is the need to elaborate further on the relationship between emerging data-driven technology solutions and environmental sustainability in connection to energy efficiency, pollution reduction, and urban metabolism. This is because the focus in the second case study is by design approach on the core environmental dimension of sustainability with reference to sustainable systems, greening, and passive solar design. And the focus in the third case study by design approach on data-driven technologies and data-oriented competences used for developing and implementing applied innovative solutions in relation to the three dimensions of sustainability. In addition, the data-driven smart city and the eco-city are increasingly being merged on the basis of the IoT and big data analytics in a bid to confront the significant challenges posed by climate change in the face of rapid urban growth.

Author's Contribution:

The four papers were entirely written by Simon Elias Bibri. John Krogstie provided comments and suggestions for improvements prior to the review process.

4.6. Contribution 6

P10: Bibri Simon Elias and Krogstie John: **"Data-Driven Smart Sustainable Cities of the Future: A Novel Model of Urbanism and its Core Dimensions, Strategies, and Solutions"**. Journal of future Studies; Volume 25(2). pp. 77–94

Abstract:

The big data revolution is heralding an era where instrumentation, datafication, and computation are increasingly pervading the very fabric of cities. Big data technologies are seen as a powerful force that has great potential for improving and advancing urban sustainability thanks especially to the IoT. Therefore, they have become essential to the functioning of sustainable cities. Besides, yet knowing to what extent we are actually making any progress towards sustainable cities remains problematic, adding to the conflicting, or at least fragmented, picture that arises of change on the ground in the light of the escalating urbanization trend. In a nutshell, new circumstances require new responses. One of these responses that has recently gained prevalence worldwide is the idea of "data-driven smart sustainable cities." This paper sets out to identify and integrate the underlying components of a novel model for data-driven smart sustainable cities of the future. This entails amalgamating the prevailing and emerging paradigms of urbanism in terms of their strategies and solutions, namely compact cities, eco-cities, data–driven smart cities, and environmentally data-driven smart sustainable cities. This amalgamation is grounded in the outcomes of the four case studies conducted on six of the ecologically and technologically leading cities in Europe. This empirical research is part of an extensive futures study, which aims to analyze, investigate, and develop a novel model for data-driven smart sustainable cities of the future using backcasting as a strategic planning process. We argue that the proposed model has great potential to improve and advance the contribution of sustainable cities to the goals of sustainability by harnessing its synergistic effects thanks to data-driven technologies and solutions. This new model is believed to be the first of its kind and thus has not been, to the best of our knowledge, produced, nor is it currently under investigation, elsewhere.

Relevance to the Thesis: P10 presents the results of the four case studies in terms of the dimensions, strategies, and solutions of the prevailing models of sustainable urbanism and the emerging models of smart urbanism. This in turn allows to identify the underlying components of the future model of urbanism and then to integrate them into the framework for strategic sustainable urban development planning proposed in P1. The intent of this applied theoretical framework (derived based on the outcomes of P6, P7, P8, and P9) is to guide the development of the novel model for data-driven smart sustainable cities of the future (P11, P12, and P13). The first part of P13 identifies the key benefits of sustainable cities and the potentials and opportunities of smart cities for boosting these benefits with respect to the three dimensions of sustainability and their balanced integration. In this respect, it highlights the added value of the future vision and thus justifies the adoption of the future model of urbanism. P10 answers RQ4 and RQ5 and the first part of P13 answers RQ6. P10 and the first part of P13 result in C6. They represent the Step 5 of the futures study.

Description of the work:

P10 identifies and distills the underlying components of the future model of urbanism in terms of its dimensions, strategies, and solutions. This is done on the basis of the results of the four case studies conducted within the frameworks of compact cities, eco-cities, data–driven smart cities, and environmentally data-driven smart sustainable cities. Subsequently, this paper combines and integrates the core components derived from these prevailing models of sustainable urbanism and emerging models of smart urbanism into an applied theoretical framework for strategic sustainable urban development planning. The argument underlying the essential elements of such framework is that the IoT and big data technologies and their novel applications as offered by smart cities of the future have great potential to enhance and consolidate the design strategies and environmental technology solutions of sustainable cities. This results in improving and advancing the contribution of sustainable cities to the environmental, economic, and social dimensions of sustainability through harnessing their synergistic effects and supporting their balanced integration. The proposed framework serves as an input to the final phase of the futures study in terms of guiding and informing the development of the novel model for data-driven smart sustainable cities of the future in the form of a strategic planning process of transformative change towards sustainability in the era of big data.

Part 1 of P13 identifies and distils the key benefits of sustainable cities and the key potentials and opportunities of smart cities with regard to the three goals of sustainability. This is also done on the basis of the results of the four case studies conducted within the frameworks of compact cities, eco-cities, data–driven smart cities, and environmentally data-driven smart sustainable cities. The outcome is intended to highlight the added value of their combination in the ambit of data-driven smart sustainable cities of the future in respect to maximizing the tripartite value of sustainability.

Author's Contribution:

The first paper was entirely written by Simon Elias Bibri. John Krogstie provided comments and suggestions for improvements prior to the review process.

4.7. Contribution 7

P11: Bibri, Simon Elias and Krogstie John: **"A Novel Model for Data-Driven Smart Sustainable Cities of the Future: A Strategic Roadmap to Transformational Change in the Era of Big Data" .** Future Cities and Environment; Volume 7(1).3 pp. 1–25

Abstract:

The conscious push for sustainable cities to be smarter and thus more sustainable in the era of big data is due to the problematicity surrounding their development planning approaches and operational management mechanisms, as well as the fragmentation of their designs and technologies. This has a clear bearing on their performance with respect to the contribution to and balancing of the goals of sustainability. This situation is compounded by the negative consequences of the expansion of urbanization, an irreversible global trend involving a multitude of environmental, social, economic, and spatial conditions that pose unprecedented challenges to policymakers and planners. The underlying argument is that more innovative solutions and sophisticated methods are needed to enable sustainable cities to tackle the kind of problems and complexities they embody. This in turn brings us to the question related to the weak connection between sustainable cities and smart cities as approaches as well as their extreme fragmentation as landscapes, both at the technical and policy levels. Therefore, sustainable cities need to embrace and leverage what smart cities have to offer so that they can optimize, enhance, and maintain their performance and thus achieve the desired outcomes of sustainability. This paper aims to develop a novel model for data-driven smart sustainable cities of the future, and in doing so, it provides a strategic planning process of transformative change towards sustainability. This *model combines and integrates the prevailing paradigms of sustainable urbanism and the emerging paradigms of smart urbanism —based on the outcomes of the four case studies conducted on compact cities, eco-cities, data–driven smart cities, and environmentally data-driven smart sustainable cities. At the core of this aggregate model is how to bring about the different forms of infrastructural transformations needed to reach a vision for a sustainable future in the era of big data. Especially, it has become feasible to attain important improvements and advancements of sustainability by amalgamating sustainable cities and smart cities thanks to the proven role of advanced ICT and the untapped potential of data-driven technologies.*

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P12: Bibri, Simon Elias: **"Data-driven Environmental Solutions for Smart Sustainable Cities: Strategies and Pathways for Energy Efficiency and Pollution Reduction" .** Euro-Mediterranean Journal of Environmental Integration; Volume (5).66 pp. 1-6

Abstract:

One of the overarching strategies of the leading environmental programs for smart sustainable cities is "resource efficiency and climate responsibility." With this strategy, smart sustainable cities aim to reduce GHG emissions to a level below 1 ton per inhabitant by 2030 and to become fossil fuel-free and climate-positive by 2050 as ambitious environmental goals. At the core of this strategy is the reduction of energy consumption and carbon footprint as well as the use of digitalization and new technologies to make it easier for citizens and businesses to be environmentally friendly. Both smart cities and sustainable cities are increasingly investing in and implementing smart meters, sensor networks, automated control systems, and cyber-physical systems in the area of smart energy and smart environment. This paper provides the key strategic pathways for achieving the goals of energy efficiency and pollution reduction. Data-driven smart solutions have significant potential to improve and advance environmental sustainability in the context of smart sustainable cities. These solutions include smart grid, advanced metering infrastructure, smart buildings, smart home appliances and tools, and smart environmental control and monitoring. There is a clear synergy between these solutions in terms of their interaction to produce combined effects greater than the sum of their separate effects with respect to the environment.

P13: Bibri, Simon Elias: **"A Novel Model for Driven Smart Sustainable Cities of the Future: The Institutional Transformations Required for Balancing and Advancing the Three Goals of Sustainability" .** Journal of Energy Informatics, Volume (4).4 pp. 1-37

Abstract:

In recent years, it has become increasingly feasible to achieve important improvements of sustainability by integrating sustainable urbanism with smart urbanism thanks to the proven role and synergistic potential of data-driven technologies. Indeed, the processes and practices of both of these approaches to urban planning and development are becoming highly responsive to a form of data-driven urbanism, giving rise to a new phenomenon known as "data-driven smart sustainable urbanism." Underlying this emerging approach is the idea of combining and integrating the strengths of sustainable cities and smart cities and harnessing the synergies of their strategies and solutions in ways that enable sustainable cities to optimize, enhance, and maintain their performance on the basis of the innovative data-driven technologies offered by smart cities. These strengths and synergies can be clearly demonstrated by combining the advantages of sustainable urbanism and smart urbanism. To enable such combination, major institutional transformations are required in terms of enhanced and new practices and competences. Based on case study research, this paper identifies, distills, and enumerates the key benefits, potentials, and opportunities of sustainable cities and smart cities with respect to the three dimensions of sustainability, as well as the key institutional transformations needed to support the balancing of these dimensions and to enable the introduction of data-driven technology and the adoption of applied data-driven solutions in city operational management and development planning. This paper is an integral part of a futures study which aims to analyze, investigate, and develop a novel model for

data-driven smart sustainable cities of the future. I argue that emerging data-driven technologies for sustainability as innovative niches are reconfiguring the socio-technical landscape of institutions, as well as providing insights to policymakers into pathways for strengthening existing institutionalized practices and competences and developing and establishing new ones. This is necessary for balancing and advancing the goals of sustainability and thus achieving a vision for desirable future.

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Relevance to the Thesis: P 11, P12, and the second part of P13 present the novel model for data-driven smart sustainable cities of the future. This takes the form of a full strategic planning process of transformative change towards sustainability, meaning the broadly defined objectives and targets, the future vision, and the strategies and pathways needed to attain it. P 11 is the main contribution to building the novel model for data-driven smart sustainable cities of the future with respect to how to bring about the necessary transformations. P12 and the second part of P13 are complementary to this contribution. P12 is concerned with the smart energy and smart environment transitions related to the essential urban infrastructure. P13 is concerned with the institutional changes necessary for supporting the balancing of the goals of sustainability and for enabling the introduction of data-driven technology and the adoption of applied data-driven solutions in city operational management and development planning. P11, P12, and the second part of P13 provide the actions that meed to be taken and the measures that need to be implemented in order to attain the vision of the future. Accordingly, they represent the analytical side of backcasting, that is, the possible ways of linking the goal of the vision of the future that lie far ahead in the future to a set of decisive steps that need to be performed now and designed to achieve the preferred future. P 11, P12 and the second part of P13 answer RQ7 and generate C7. They represent the step 6 of the futures study.

Description of the work:

The final contribution of the PhD study is concerned with the analytical side of backcasting. This is referred to in futures research as backwards-looking analysis, the specific step of looking back from the desired future to the present to determine the decisive steps on how to attain the future vision, addressing various dimensions. In including the broadly defined objectives and targets and the future vision, P11 provides a strategic planning process of transformative change towards urban sustainability, having all the necessary parts. And in doing so, it develops a novel model for data-driven smart sustainable cities of the future. The overall landscape of the data-driven smart sustainable city of the future consists of five dimensions, namely built infrastructure, sustainable urban infrastructure, smart urban infrastructure, social infrastructure, and technological infrastructure. These are associated with the transformations that are necessary for reaching he future vision. In order to bring about these transformations, this paper develops a number of strategies and pathways. The latter represent a set of recommendations in the form of planning actions and policy measure to the strategic stakeholders of the city of the future. These recommendations represent the key outcomes of the case study research conducted.

Worth pointing out is that the final step of the futures study was too long to be included in one single paper, thereby dividing its outcome into three papers instead. Given its scope, P11 constitutes the main contribution to the analytical side of backcasting. P12 and Part 2 of P13 are complementary in this regard. P12 develops the strategies and pathways needed to enable the transitions associated with energy efficiency and pollution reduction in connection with the smart urban infrastructure. Part 2 of P13 identifies the core institutional changes necessary for supporting the balancing of the goals of sustainability and for enabling the introduction of data-driven technology and the adoption of applied technology solutions in urban operational management and development planning. It was concluded that the emerging data-driven technological changes for sustainability are reconfiguring the broader socio-technical landscape of politics, policy, and institutions, as well as providing insights to policymakers into pathways for strengthening existing institutionalized practices and competences and developing and establishing new ones. The intention is to achieve a balanced and synergistic integration of the three dimensions of sustainability, thereby boosting the benefits of sustainability as to its tripartite composition. This can be accomplished by combining and consolidating the design strategies and environmental technology solutions of sustainable cities and the data-driven technologies and solutions of smart cities.

Backcasting as a form of strategic planning is about figuring out the "next steps," which are quite literally the next concrete actions and measures to undertake. While the next steps are usually based on responding to the present circumstances, creativity, and common sense, they are still aligned with the future vision. The planning process serves as a tool for facilitating progress towards achieving the goals of sustainability for those cities that are badging or regenerating themselves as sustainable, or manifestly planning to be or become smart sustainable in the era of big data.

Author's Contribution:

The three papers were entirely written by Simon Elias Bibri. John Krogstie provided comments and suggestions for improvements prior to the review process in reference to P11 and P12.

5. Results

This chapter focuses on the main outcome of the entire research conducted in the PhD study, as described in Chapter 4. That is, the results that are associated with the most important contribution of the PhD study—the novel model for data-driven smart suitable cities of the future. This represents a strategic planning process of transformative change towards sustainability based on backcasting. As a roadmap to transformational change, the backcasting process articulates strategic thinking—the why—behind both the vision of the future and the plan for getting there. Strategic planning denotes a systematic process of generating a vision for a desirable future and translating it into broadly defined objectives and targets, and then identifying a sequence of actions and measures to achieve that specified future. Accordingly, this chapter is structured into three main phases: (1) the vision of the future, (2) the objectives and targets related to sustainability, and (3) the strategies and pathways for transformative change towards sustainability.

5.1. Phase 1: The Future Vision

5.1.1. The Normative Side of Backcasting

The vision of the future is where the problems, issues, and challenges related to sustainable cities have been solved by means of the data-driven technologies and solutions offered by smart cities of the future. However, the overall goal, which builds the vision of what the future should look like once manifested, is the indicator established to determine whether the objectives have successfully been achieved. The data-driven smart sustainable city of the future is envisaged as:

"*A form of human settlements that secures and upholds environmentally sound, economically viable, and socially beneficial development through the synergistic integration of the more established strategies of sustainable cities and the more innovative solutions of data-driven smart cities towards achieving the long-term goals of sustainability*."

The future vision entails retaining the best of what we already have that have been successfully enacted in real-world cities, making use of the things that have been demonstrably better in the past, while being selective in adopting the best of what is emerging and promising, making use of the things that will add a whole new dimension to sustainability in terms of harnessing its synergistic effects, balancing its dimensions, and thus boosting its benefits.

5.1.2. The Key Benefits, Potentials, and Opportunities of the Future Vision

One of the goals that is necessarily present in most backcasting studies addressing urban sustainability is analyzing the benefits, potentials, and opportunities of the future vision. That is, the results of environmental, economic, and social analyses in relation to urban sustainability. Based on the outcomes of the four case studies conducted on the prevailing paradigms of sustainable urbanism and the emerging paradigms of smart urbanism, numerous benefits of eco-cities and compact cities have been realized and many potentials and opportunities of emerging data-driven smart cities and environmentally data-driven smart sustainable cities are being unlocked and exploited. The purpose of their identification is to highlight the added value of their combination within the framework of the data-driven smart sustainable city of the future in regard to maximizing the tripartite value of sustainability. This is by means of integrating the design strategies and sustainable technologies of sustainable cities with the data-driven technologies and solutions of smart cities.

The key benefits, potentials, and opportunities of the future vision are presented next in accordance with the four paradigms underlying the data-driven smart sustainable city of the future.

Compact Cities: The compact city is the most advocated model of sustainable urban form due to its ability to deliver the expected benefits of environmental, economic, and social sustainability, yet to varying degrees (Table 5.1).

Environmental sustainability
• Lowering per capita rates of energy use and CO_2 emissions through district-wide energy utilization and local energy generation
• Conserving energy by combining heat and power provisions made possible by population densities
• Lowering energy consumption and reducing pollution due to the proximity to workplaces, services, facilities, and public spaces
• Reducing car dependency and thus CO_2 emissions through promoting a walking and cycling environment
• Decreasing travel needs and costs and shortening commute times
• Minimizing the transportation of energy, materials, water, and products, thereby reducing CO_2 emissions due to the compactness of the built form
• Optimizing the efficiency of public transport by promoting transit-oriented development in built-up areas
• Limiting the consumption of building and infrastructure materials
• Reducing the pressure on ecosystem services and biodiversity provided by green and natural areas
• Limiting the loss of green and natural areas
• Protecting rural and agricultural land from further development through the optimum use of land resources
Economic sustainability
• Supporting local services and businesses through population densities by providing a larger customer basis for commercial activities
• Revitalizing city centers through the promotion of densely built dwellings, shops, businesses, and accessible infrastructure and facilities
• Extending and enhancing public transportation infrastructure and facilities
• Creating proximity between workers and their workplaces, which results in higher productivity due to shorter travel time
• Greater diversity of employers and thus job possibilities
• Increasing the likelihood of workers finding jobs that match their skills, which also results in higher productivity
• Attracting skilled labor force by high quality of life due to better access to a diversity of local services and jobs
• Maintaining the diversity for choice among workplaces, service facilities, and social contacts
• Requiring less and cheaper per capita infrastructure provision due to more efficient public service delivery
Social sustainability
• Creating a better quality of life through more social interaction, community spirit, and cultural vitality due to the access by proximity to facilities, workplaces, public spaces, public transportation, as well as the opportunity for walking and cycling
• Reducing crime and providing a feeling of safety through natural surveillance
• Improving social equity through better access to services and facilities and flexible design of housing in terms of mixed forms and affordability
• Maintaining public service level for social welfare by improved efficiency
• Greater accessibility due to lower cost enabled by shorter intra-urban distances
• Lowering transport costs, higher mobility for people without access to a car, and improved human health due to more cycling and walking
• Enhancing social cohesion through a sense of belonging and connectedness
• Supporting human, psychological, and physical health through ready access to open green space, walkability in neighborhoods, and social contact
• Enhancing livability in terms of social stability and cultural and recreational possibilities
• Healing spatial segregation by forging the physical links and bridging barriers between communities

Table 5.1 The contribution of the compact city to the three goals of sustainability

Eco-Cities: The eco-city focuses more on the environmental dimension of sustainability in terms of the natural environment and ecosystems than on the economic and social dimensions of sustainability.

Accordingly, while the benefits of the eco-city are mostly of an environmental nature, they also include some economic benefits pertaining to green technologies (Table 5.2).

Green infrastructure

- Providing ecosystem services:
  - Air quality
  - Recreation
  - Climate mitigation and adaptation
  - Flood risk mitigation by slowing and reducing stormwater discharges
  - Temperature regulation
  - Passive irrigation
  - Biodiversity and habitat
  - Stormwater management
- Managing water by mimicking the natural water cycle
- Improving the quality of water by protecting local waterways from stormwater pollutants
- Replacing or complementing technical systems
- Making urban areas more pleasant by improving their design aesthetics
- Improving economic attractiveness through greening, e.g., high land values that create a willingness to invest and develop urban areas
- Enhancing community safety and the quality of life
- Removing harmful substances from the air and thus increasing its quality
- Reducing stress as linked to mental and physical well-being and the development of illness.
- Providing favorable conditions for healthier life
- Reducing traffic noise and providing cooler temperatures and greater diversity

Sustainable energy systems

- Maximizing energy efficiency
- Conserving energy by combining heat and power provisions
- Reducing CO2 emissions due to the use of renewable energy sources:
  - Wind, solar, and hydropower produce little or no air pollution
  - Biomass and geothermal do emit air pollutants, but at much lower rates than most fossil fuels
- Enabling districts to become fossil fuel–free, zero-carbon, and climate positive
- Reducing energy costs and ecological impact to the lowest possible level
- Diversifying energy supply and reducing dependence on imported fuels
- Enabling cheap and clean energy system management
- Mitigating large-scale failure due to a distributed, modular fashion deployment
- Distributing electricity with less complex and time-consuming infrastructural development thanks to the quick rollout of technologies in response to the needs of the city during critical events or complex emergencies

Sustainable waste management system

- Decreasing the landfilling of household waste and other waste
- Rising the recovery of material for reuse and recycling, as well as of energy in the form of heat and electricity
- Generating biogas fuels from food sludge and other organic waste as well as from wastewater and sewage
- Converting food waste into bio–fertilizer that can replace artificial fertilizers
- Mitigating Greenhouse Gases (GHG) emissions from waste incineration, irrespective of the quantity of the incinerated waste
- Reducing he environmental impact of waste management: GHG emissions and emissions of hazardous substances (e.g., organic pollutants, heavy metals)
- Reducing the noise and congestion caused by garbage collection trucks thanks to the bins connected directly to the underground repositories, where waste is sucked out by vacuum chutes via underground pipes

Sustainable materials

- Increasing productivity
- Improving health and quality of life
- Decreasing waste generation
- Using materials in more effective ways
- Reducing air pollution
- Avoiding noise pollution

Green technology development

• Spurring green-tech innovations • Increasing green-tech manufacturing and export • Stimulating R&D projects and opportunities • Inspiring entrepreneurship and creating startups • Increasing industrial and technological investments • Providing a significant number of jobs and opportunities for skill development • Stimulating cooperation between government, industry, and academia • Providing opportunities for international collaboration among urban actors

Table 5.2 The key environmental and some economic benefits of the eco-city

Data-Driven Smart Cities and Environmentally Data-Driven Smart Sustainable Cities: As emerging models of urbanism, data-driven smart cities and environmentally data–driven smart sustainable cities involve not only benefits, mostly related to eco-cities, but also potentials and opportunities, which are yet to be exploited and explored respectively (Table 5.3).

Smart transport and traffic management
• Reducing energy usage and harmful emissions • Providing the opportunity to alter demand for carbon-intensive vehicles using disincentives • Increasing and maintaining safety for vehicle drivers by detecting accidents and responding timely to critical events through alerts • Predicting traffic conditions for decreasing congestion by directing vehicles to alternative roads • Reducing noise pollution through smart traffic lights and smart parking • Improving the security and reliability of the overall transport system • Encouraging and attracting people to cycle thanks to dynamic signage system, thereby reducing CO2 emissions resulting otherwise from more polluting forms of energy-intensive transport • Enhancing mobility for citizens and thus increasing the level of their life satisfaction • Providing the opportunity for contactless payment and thus minimizing environmental impacts • Providing the opportunity for obtaining more detailed information on transport and mobility thanks to the unified public transport system • Tracking traffic occupancy for planning public transport routes in a more flexible way • Identifying the user priorities of public transport areas and developing new routes in response to new demands • Improving, re–engineering, or developing transport infrastructure based on historical mobility and congestion data • Decreasing the need for parking spaces on the streets through car sharing system • Supporting equity and inclusion through socially sustainable public transport thanks to smart mobility apps • Providing information to passengers about traffic occupancy/irregularities of public transport, which allows them to plan their way more efficiently
Smart power grid

- Improving the transmission efficiency of electricity
- Optimizing distribution networks in terms of energy demand/supply
- Restoring after and reacting timely to potential disturbances in power supply
- Reducing operation, maintenance, and management costs
- Integrating different systems of renewable energy
- Reducing electricity bills and thus saving money as well as balancing the electricity system through efficient electricity networks
- Making storage decisions based on the monitoring of power generation and power demands
- Helping governments to react promptly to emergencies, critical events, or natural disasters, e.g., severe storms, earthquakes, and large solar flares, through adding resiliency to large-scale power systems
- Curbing energy usage, conserving energy, reducing costs, and maximizing the transparency and reliability of the energy supply chain
- Avoiding potential power outages resulting from high demand on energy using dynamic pricing models for power usage by increasing charges during peak times to smooth out peaks and applying lower charges during normal times.
- Avoiding carbon–intensive peaks using new ways of coordination with regard to the overall ensemble of users and consumers.
- Supporting decision–making pertaining to the generation and supply of power in line with the actual demand of users and consumers
- Improving coordination and planning around power generation from renewable plants depending on wind or sun.
- Monitoring and analyzing energy consumption in real time across multiple spatial scales and over different temporal scales

Smart buildings

- Providing the potential for energy efficiency and GHG emissions reductions through such functions as:
  - Highly advanced automatic systems for efficient and natural lighting
  - Temperature control
  - Window and door operation
  - Smart appliances
- Keeping the building's climate within a specified range
- Reducing energy consumption and energy costs
- Guaranteeing safety and security
- Providing the potential for decreasing heat demand and consequent GHG emissions by means of retrofitting residential buildings
- Assessing energy demand from large-scale retrofitting and exploring its impact on the supply side, thereby enabling more precisely targeted and better coordinated energy efficiency programs

Smart meters and energy monitors

- Allowing consumers to manage their energy usage based on what they actually need and afford by having access to live energy prices and adjusting their usage accordingly
- Enabling consumers to remotely control their home appliances and devices by means of such advanced functions as scheduling, programming, as well as reacting to contextual situations
- Allowing for self–optimization and self–control of energy consumption through integrating sensing and actuation systems in different kinds of appliances and devices for balancing power generation and usage
- Providing insights into how the energy flows can be influenced by the consumer behavior thanks to the in-house sensors that can report data on energy-using appliances
- Balancing electric loads and reducing power outages
- Allowing for dynamic pricing that lowers or raises the cost of electricity based on the current demand
- Providing homeowners with convenience and cost savings
- Offering homeowners sophisticated level of preprogrammed preferences in terms of turning on some appliances based on the amount of the energy consumed within a day, week, or month

Smart environmental monitoring

- Reducing the time needed for waste collection as well as the operating time of disposal machines
- Curbing fuel consumption and costs
- Reducing the number of waste disposal vehicles and containers and related service costs
- Reducing the level of harmful emissions through route optimization
- Decreasing noise pollution generated by waste disposal vehicles
- Providing health benefits and decreasing health risks through preventing the accumulation of waste
- Using historical and movement data
- Using historical data on disposed waste (places and volumes) for installing new waste containers
- Distributing the resources and logistics more efficiency, thereby significantly reducing the operational and infrastructural costs of waste collection system

Smart management of waste collection
• Developing a variety of preventive systems and measures for environmental quality and implementing them in a timely manner • Enabling public authorities to observe the condition of the air and to forecast about its pollution • Enabling government and non-governmental bodies to take decisions based on a more informed understanding of the quality of the environment • Complementing energy efficiency solutions with respect to GHG emissions reductions • Informing citizens and other city stakeholders about GHG emissions • Ensuring companies' compliance with environmental regulations and evaluating the efficiency of the newly installed systems as well as the health of employees • Evaluating the performance of environmental regulations and enforcements, whether they are working as anticipated, so that the government can take action to change the regulatory framework • Stimulating research opportunities on the effects of certain pollutants on human, wildlife, or aquatic life so to create treatment procedures • Finding risks to human and wildlife, scoping to population migration from high-density areas to low density areas, and restricting GHG emissions • Identifying environmental stress, understanding environmental patterns, and assessing the effectiveness of strategies and programs • Collecting critical information to make better policy decisions to reduce GHG emissions, as well as to guide citizens on making their own efforts in this regard • Allowing the interpretation of the ambient air data based on the spatial and temporal representativeness of the data gathered and on the health risks involved in the exposure to the monitored levels • Allowing the comparison of the different districts of the city in terms of various air pollutants • Publishing hourly more detailed information for each pollutant in absolute value, and designing daily values for drawing a more complete picture at monitoring the level of pollution in the city • Allowing users to explore the available information at maximum level due to the opportunity to gather information about the status of the atmosphere • Allowing companies and enterprises in the industry to get an idea about the air quality, which makes it possible to make decision on the implementation of preventive measures for reducing pollution. This leads to the maximisation of their productivity in the long-term • Allowing industries to access the air pollution forecasts, which simplifies the decision-making process in the manufacturing environment • Predicting trends of the presence of air pollutants in the atmosphere • Coping with the environment and lowering air and noise pollution levels to enhance the quality of life
Smart street lighting
• Facilitating many innovative applications related to traffic, mobility, air and noise pollution, parking, safety, and public Wi-Fi connectivity, just to name a few • Enhancing the environmental performance and energy efficiency of the essential infrastructure of the city • Optimizing the efficiency of the public-lighting installations in terms of operational and maintenance costs • Reducing collision and the risk of collisions with cyclists and other vulnerable road users
Smart urban metabolism
• Providing holistic analysis of energy and material pathways to conceive of management systems and technologies that allow for the reintegration of natural processes, increasing the efficiency of resource use, and the conservation and production of energy • Providing long–term opportunities in terms of enabling a new understanding of the causalities that govern urbanism • Allowing citizens and city officials and stakeholders to receive real-time feedback on the consequences of their choices in a systematic way • Understanding the GHG emissions resulting from the consumption of electricity, heat, water, and the production of waste • Allowing the follow-up and evaluation of the evolution of urban metabolism, and facilitating the identification of the cause-and-effect relationships of the metabolic flows • Providing rich datasets on energy and material flows at the city level in terms of both production- and consumption-based approaches
Smart management of urban infrastructure

• Improving incident management • Enhancing emergency response coordination • Mitigating risks and responding timely to critical events or unfavourable conditions • Enhancing safety and service quality • Reducing operational and maintenance costs • Improving resources and logistics efficiency • Reducing negative impacts on the environment • Identifying, predicting, and responding to longer-term urban infrastructure needs	
Smart citizens: participation and consultation	
• Empowering citizens for community engagement and co-creation • Improving the level of satisfaction and increasing the level of confidence and trust among citizens in the city administration • Promoting widespread participation through new technologies that are essentially network-based and enable extensive interactions across many urban domains as well as spatial scales • Enhancing equity and fairness and attaining a better quality of city life through new technologies that offer the prospect of ending the digital divides • Enabling the citizenry to blend their personal knowledge with the knowledge of technology experts • Informing political participation at all levels • Engaging the citizenry in city planning, development, and governance • Making it easier for citizens to find out about planning issues and improving the efficiency and effectiveness of local planning • Enabling the planning service to perform better with fewer resources for property developers, architects, surveyors, and planning consultants • Improving the transparency of the city management • Providing the opportunity to track the quality of work of the management companies and contractors engaged in the provision of urban amenities and services, and to perform corrective actions in the work of local authorities • Enabling citizens to participate in the technology and policy of the city through various platforms, such as classrooms for leaning, spaces for innovation, co-innovation centers, and participatory and democracy platforms • Providing services by public agencies remotely and mobile kiosks, such as receiving certificates, publishing complaints, and obtaining necessary information. This improves the convenience of public services • Determining trends in public opinion to be considered when forming urban development programs and initiatives	
Smart public safety	
• Empowering decision-makers to prepare for, respond to, and recover from natural disasters • Increasing safety by identifying risks, threats, and vulnerabilities and providing early warnings • Preventing adverse effects on public health by notifying citizens to evacuate or avoid certain urban areas • Enhancing risk assessment and hazard identification to provide immediate responses • Improving security by allowing or denying access to certain individuals to public places, as well as preventing potential unrest • Providing the opportunity for increasing urban resilience • Informing the responsible public and private actors of transportation–related safety and health issues to make improvements	
Smart healthcare	

- Electronization of medical services:
  - Making medical services more accessible to the public
  - Accelerating the process of customer services
  - Allowing more flexible arrangement of visits to doctors and obtaining the right specialist
  - Enabling physicians to get rid of paper routine and to always have access to data about patients, the history of their diseases, and the medicines they take
  - Providing the municipal administration with reliable and efficient tools for analysis of medical institutions activities
  - Providing the administration with the opportunity of managing resources more efficiently
  - Enabling transparent reporting and planning for future purchases and saving costs for the city budget.
- Large-scale electronization system:
  - Improving the comfort of using public medical services
  - Optimizing the availability and workload of physicians in medical institutions
  - Enabling managing flows of patients and outpatient integrated medical records
  - Keeping consolidated management records and personalised accounts of medical assistance
  - Making online and rescheduling appointments
  - Checking-in without preliminary cancellation and obtaining medical certificates online
  - Finding the nearest clinic nearby place of residence
  - Gathering information about the workload of medical institutions and the demand for doctors
  - Managing medical registers and solving medical and organisational tasks relating to different categories of citizens, those with certain diseases.
- Enhancing diagnosis and treatment processes and tailoring care services
- Providing precautionary and proactive care services
- Prolonging human life and promoting human well-being
- Enabling remote services such as diagnosis and telemedicine
- Improving the quality of recommendations and reducing the time spent on making them as well as on diagnostics
- Providing accurate, appropriate, and history-aware responses to health problems
- Flagging potential health issues frequently or on a demand basis by monitoring, processing, and analyzing complex occurrences
- Predicting and responding to disease outbreaks, critical events, and new trends

Table 5.3 The key benefits, potentials, and opportunities of the data-driven sustainable smart city

5.2. Phase 2: The Targets and Objectives

The future vision is translated into broadly defined objectives and targets, which are of a long-term nature. The objectives and targets can also be used to develop the future vision. However, as with the future vision, these objectives and targets were refined in light of the new theoretical and practical knowledge gained from carrying out the case study research. The targets are established first as specific desired outcomes that support the achievement of the objectives. These define an endpoint of concern and the direction of change that is preferred. The targets and objectives are to be—specific, measurable, achievable, relevant, and targeted when adopting the future model of urbanism. They are decided on according to what the data-driven smart sustainable city of the future aspires to achieve, an ambition that can be adapted to existing sustainable cities in their own contexts.

The objectives describe the measurable contribution of the data-driven smart sustainable city of the future as to achieving the overall goal of the future vision. Therefore, they define what is to be achieved and should have a specified timescale and be linked to the performance of the data-driven smart sustainable city of the future to ensure that policy commitments are prioritized and addressed in terms of improving and advancing the environmental, economic, and social goals of sustainability. This improvement should also be continual in line with sustainability policies in relevance to the national and local context of existing sustainable cities so that new objectives can be agreed on when the original objectives have been met. However, the objectives are of a qualitatively descriptive nature because the future vision is not concerned with a given sustainable city, or departs from a basic standard in mind accordingly. With that in regard, the data-driven smart sustainable city of the future aims to achieve the objectives of sustainable development, the most prominent among them are presented in Table 5.4.

- Reduced energy consumption and carbon footprint
- Improved resource efficiency with minimal environmental impacts
- Minimized waste
- Increased use of sustainable materials
- Reduced air and noise pollution
- Reduced automobile use
- Preservation of open space and sensitive ecosystems
- Improved social justice and equity
- Enhanced quality of life and well-being
- Liveable and community-oriented human environments

Table 5.4 The prominent objectives of sustainable development

The targets are the indicators that are established to determine how successfully the objectives have been achieved by providing relevant benchmarks for the compact, ecological, and technological components of the data-driven smart sustainable city of the future. This involves how synergistically these components are integrated, cooperate, and beneficially complement one another. The targets can quantify or qualify the objectives over time. The specific targets set in relation to the future vision are specified in terms of the dimensions, strategies, and solutions of the four investigated models of urbanism. However, similar to the objectives, the targets are of a qualitatively descriptive nature because the future vision is not concerned with a given sustainable city, or departs from a basic standard in mind accordingly. The future vision as a long-term goal represents the set of targets that should move the city from its current state (sustainable) to its future state (data-driven smart sustainable). Hence, these targets incorporate the objectives of sustainable development as well as the objectives of technology associated with the readiness of the city to introduce data-driven technology in, and the implementation of applied technology solutions for, city operational management and development planning with regard to sustainability. Accordingly, they should be based on the synergistic integration of the strategies and solutions of the four investigated models of urbanism (Table 5.5)

- Increased compactness of urban space
- High density and diversity of buildings
- Multidimensional mixed uses: social mix, physical land use mix, economic mix, and temporal mix
- Prioritized sustainable transportation and its integration with smart transportation
- Multifunctional green infrastructure for ecosystem services and biodiversity
- Balanced mixture of low-energy, energy-efficient, and passive buildings
- Large–scale net–zero and locally produced solar energy houses
- Sustainable energy system and its integration with smart energy system
- Sustainable waste system and its integration with smart waste system
- High degree of the readiness of the city to the integration of advanced technology in its management:
  - High availability and development level of the infrastructure and big data analytics competencies required for the functioning of the city
  - New and extensive sources of data and a high level of support for open and standard data
- High degree of the implementation of applied technology solutions for the city management:
  - High level of the development of applied data-driven solutions for the city operational management and development planning related to the various areas of sustainability
  - Established data-oriented competences pertaining to research, innovation, strategic planning and policy, education, and professional training.

Table 5.5 The compact, ecological, and technological targets of the future model of urbanism

Worth noting is that the above stated targets embody the targets of the SDG 11 (Table 5.6). These are slightly adapted from the United Nations (2015a) as the focus of the futures study is on the cities that are already badging or regenerating themselves as sustainable, or manifestly planning to be or become smart sustainable.

1.	Ensure access for all to adequate, safe, and affordable housing and basic services.
2.	Provide access to safe, affordable, accessible, and sustainable transport systems for all.
3.	Enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management.
4.	Strengthen efforts to protect and safeguard the natural and cultural heritage.
5.	Reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.
6.	Provide access to safe, inclusive and accessible, green and public spaces.
7.	Substantially increase the number of human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation of and adaptation to climate change, and resilience to disasters.

Table 5.6 The SDG 11 targets embodied in the future vision
Source: Adapted from United Nations (2015a)

5.3. Phase 3: Strategies and Pathways for Transformative Change towards Sustainability

This phase represents the analytical side of backcasting, i.e., the specific step of looking back from the desired future to the present to determine the decisive steps on how to attain the future vision. As such, it entails building a feasible and logical path between the state of the future and the present based on the criteria defined for the future vision. Such path represents a set of strategies and pathways to be pursued in order to bring about the needed transformative change towards sustainability. At the heart of these strategies and pathways is the practice-oriented process of designing and developing the data-driven smart sustainable city of the future. Different multiple strategies are needed in order to attain the future vision. To employ each of these strategies in turn requires a set of specific actions, sequences of actions, and agendas within each strategy, ways of achieving specified results. The strategies as a form of long-term plan may need to pivot in response to different external factors, such as global trends and technological shifts. The pathways are the most flexible in terms of adjustment and modification.

Important to note is that the strategies and pathways developed are informed and guided by the applied theoretical framework for strategic sustainable urban development planning derived based on the outcomes of the four case studies carried out on the prevailing models of sustainable urbanism and the emerging models of smart urbanism, namely compact cities, eco-cities, data–driven smart cities, and environmentally data-driven smart sustainable cities. This integrated framework illustrates the combination and integration of the underlying components of the future model of urbanism in terms of its core dimensions, strategies, and solutions (Figure 5.1). In this respect, there are four basic categories and criteria that are used in defining the data-driven smart sustainable city of the future: (1) compact urban strategies, (2) ecological urban strategies, (3) data-driven technologies and solutions for sustainability, and (4) data-oriented technical and institutional competences.

As illustrated in Figure 5.1 the data-driven technologies and solutions (left side) offered by smart cities can be adopted by the administration of sustainable cities to improve sustainability, efficiency, resilience, equity, and the quality of life. This requires the establishment of the urban center, labs, and offices (right side) associated with operational management and development planning. These entities represent technical and institutional competences that determine the degree of the readiness of the administration of sustainable cities to introduce data-driven technology in their management and to the degree of the implementation of applied technology solutions for their management. The degree of readiness is characterized by the availability and development level of the technological infrastructure and competencies needed to generate, transmit, analyze, and visualize data. The degree of implementation demonstrates the extensiveness of the use of the applied technology solutions developed for operational management and development planning to improve the different aspects of sustainability. These are associated with the compact (left side) and ecological (right side) dimensions of sustainable cites. The relationship between smart cities and sustainable cities enabled by big data technologies represents data-driven smart sustainable cities (oval shape).

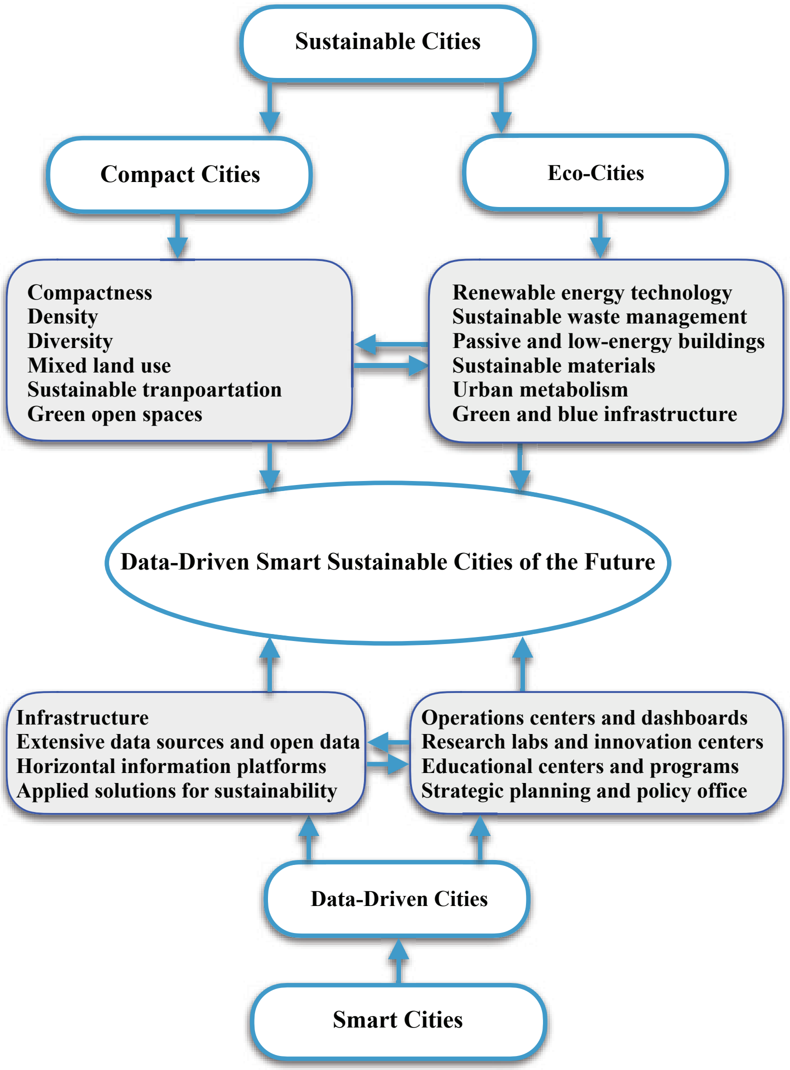

Figure 5.1 A framework for strategic sustainable urban development planning

However, developing the strategies and pathways needed to attain the vision of the future means developing the novel model for data-driven smart sustainable cities of the future in the form of a strategic planning process of transformative change towards sustainability. The key strategies are introduced and described next in accordance with the five dimensions of the landscape of the data-driven smart sustainable city of the future, namely:

1. Built infrastructure
2. Sustainable urban infrastructure
3. Smart urban infrastructure

4. Social infrastructure
5. Technological infrastructure

As far as the pathways for executing these strategies are concerned, they are addressed in more detail in P11, P12, and P13 (see Appendix A).

5.3.1. Built Infrastructure

The built infrastructure involves the patterns of the physical objects in the city pertaining to the built-up areas as well as those areas planned for new development and redevelopment together with transport, communication, anergy, and waste systems. The compact and ecological dimensions of urban design characterize most of the built infrastructure as regards its houses, buildings, blocks, streets, walkways, roads, open space, public space, green space, and urban infrastructure. Within the area of public health, the built infrastructure involves developing, enhancing, or renovating urban areas to improve the community's well-being through the construction of aesthetically, environmentally, and health improved landscapes and living structures. It is worth noting that the built infrastructure is the single biggest source of global energy consumption, and buildings are responsible for at least one-third of global GHG emissions.

Compact Design of Urban Form Strategies: Urban form refers to the physical characteristics that make up the built-up areas in a city, including shape, size, design, and configuration. The aggregation of these more or less repetitive elements represents the urban pattern. This gives a regular form to the physical objects in a city. The form of the city is seen as a salient factor for enacting more sustainable, efficient, equitable, and livable urban environments though design. It is associated with the development strategies related to urbanization dimensions, namely physical (land use change), geographical (population), economic (agglomeration), and societal (social and cultural change). These largely pertain to the design strategies of the compact city, namely:

- Compactness
- Density
- Multidimensional mixed-land use
- Sustainable transformation
- Green open space.

Ecological Design of Urban Form Strategies: Ecological design is a design form which integrates itself with living processes to minimize environmentally negative or destructive impacts. At the core of ecological design is the green structure, which is a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services, such as water purification, air quality, space for recreation, climate mitigation and adaptation, flood protection, temperature regulation, biodiversity, and local stormwater management. Green structure includes large green spaces, waterways and streams, shorelines, parks, natural land, and forests as one common structure. Green space includes trees, grassy patches, water features, flowerbeds, rock gardens, sports fields, woods, and lakesides. The green structure strategy emphasizes the benefits and losses of green structures and map green resources by assessing their natural and recreational qualities. It can be broken into the following substrategies:

- Greening
- Rainwater harvesting
- Ecological diversity
- Biodiversity
- Green parks

- Green streets and alleys
- Green factor and green points
- Green roofs and rain gardens
- Bioswales and permeable pavements

These substrategies can be implemented as part of the individual urban development projects related to the compact urban fabrics mentioned earlier, when it is feasible from a design perspective. However, the green structure strategy relates to the idea of letting nature do the work by designing multifunctional green structure to provide important ecosystem services of various categories, including provisioning, regulating, cultural, and supporting services, to reiterate. To let nature do the work entails ensuring that greenery and water are used as active components in the design and operation of the city. The green structure replaces and complements technical systems, creates a richer plant and animal life, and contribute to human health and well-being. Important to note is that the green structure strategy as an integrated approach is best to be implemented in new urban areas or outer areas with development potential.

5.3.2. Essential Urban Infrastructure: Smart and Sustainable Strategies

As a wide-ranging term, infrastructure is the basic structure that supports the operation of a city. This makes economic and social development possible. The focus here is on the essential sustainable and smart infrastructures that make up the city, including transportation systems, communication systems, energy systems, waste systems, lighting systems, sewage systems, and waste disposal systems. These are associated with the basic facilities, services, and installations needed for the functioning of the city in terms of engineered systems. As the underlying structural foundation of the data-driven smart sustainable city of the future, all infrastructural developments involve the provision of public services and the use of public spaces that are essential to the ability of people to live in the city as well as to its the healthy and continuous operation. This relates to sustainability as one of the key concepts in urban infrastructure in terms of the key issues that planners have to consider when deciding what infrastructure is needed in a given urban area. Sustainability in this context means that the infrastructure will be capable of supporting the environmental, social, and economic needs of the city, assuming that it is maintained properly. Worth pointing out is that the essential urban infrastructure embodies economic infrastructure, the internal facilities of the city that make business activity possible or promote economic activity, such as communication, transportation, distribution networks, and energy supply systems. The essential urban infrastructure involves the following strategies:

- Smart sustainable transportation
- Smart sustainable energy
- Smart sustainable waste management
- Smart urban metabolism
- Smart street lighting
- Smart urban infrastructure

Smart Sustainable Transportation: To be able to effectively strategically advance and maintain the contribution of the data-driven smart sustainable city of the future to the goals of sustainability, it is necessary to fully integrate sustainable transportation system with smart transportation system. Accordingly, the smart sustainable transportation strategy encompasses the following substrategies:

- Walking and cycling
- Public transport
- Car-pooling (biogas and electric)
- Electric vehicles
- Smart transport management

- Smart traffic management
- Smart mobility management

Sustainable transportation is a major strategy for achieving sustainability. It denotes any means of transportation that is green and has low impacts on the environment. Almost all master plans for major sustainable cities and smart cities emphasize the important relationship between planning and sustainable transportation. Sustainable transportation services reflect the full social and environmental costs of their provision and balance the needs for mobility and safety with the needs for access, livability, and environmental quality. Smart transportation is one of the main ways modern cities can improve the daily lives of citizens and its environmental, economic, and social sustainability. It involves information systems that collect data about traffic, vehicles, and the use of different modes of transport for further processing and analysis. Transport and traffic management is one of the most common areas that use data-driven technology solutions.

Smart Sustainable Energy: The smart sustainable energy strategy aims to reduce energy consumption, increase renewable energy adoption, and decrease carbon footprint, as well as to use digitalization and new technologies to make it easier for citizens and businesses to be environmentally friendly. Here technological innovations can play a prominent role in the light of the escalating trend of urbanization. Integrating sustainable energy with smart energy will drive the data-driven smart sustainable city of the future to become fossil fuel–free and climate positive. Therefore, the energy system should combine green energy technologies and energy efficiency technologies. The smart sustainable energy strategy involves the following substrategies, with some overlaps among them:

- Renewable energy sources and technologies
- Smart power grid and advanced metering infrastructure technologies
- Smart building technologies
- Smart home monitoring technologies
- Smart environmental monitoring technologies.

As regards renewable energy sources and technologies, it is important to strongly advocate renewable energy generation and usage in order to enable the data-driven smart sustainable city of the future to become fossil fuel–free by 2050. Renewable energy is derived from naturally replenished and zero-emission sources, such as solar, wind. biomass, hydropower, and geothermal), using a number of industrial and technological systems including solar collectors, solar panels/photovoltaic cells, pumps (aquifer and sea water), wind turbines, and bio–fueled combined heat and power (CHP) system.

Concerning smart grid and advanced metering infrastructure, both smart cities and sustainable cities are increasingly investing in and implementing smart meters, sensor networks, automated control systems, and cyber-physical systems in the area of smart energy within the framework of the IoT. The goal of smart energy is to achieve energy systems that are highly energy-efficient, increasingly powered by renewable and local energy sources enabled by new technologies, and less dependent on fossil fuels. The main components in the area of smart energy are the smart power grid and the advanced metering infrastructure. The former deploys smart meters and communication technologies within electricity networks. It denotes a set of hardware, software, and network tools that enable generators to route power more efficiently to consumers, reducing the need for excess capacity and allowing two–way communication for real-time demand side management. It collects the data received from Wi-Fi enabled sensor network on the level of power supply from diverse sources and then processes and analyzes these data in real-time for decision-making and information transmission for process control to improve the performance of the grid. The latter is a composite technology that consists of solid-state meters capable of remotely providing consumers' electricity use detail (i.e., electric energy, voltage levels, current, power factor) to the utility, a two-way communications channel (i.e., to power suppliers for system monitoring and billing and to consumers for greater clarity of consumption behavior), and a meter data repository and management. Thus, it includes sensors placed on consumers access points and on production, transmission, and distribution systems, as well as remote controls and communication technologies within electricity networks. The operational functioning of the smart power grid system involves ICT system integration, data, and back office, which allow the integration of front-end engineering, middleware, and computing systems, as well as data collection and decision analytics.

Smart buildings use sensors and controls in buildings to improve efficiency. The building management system (BMS), an overarching computer-based control system (an intelligent distributed network of electronic devices and systems), is responsible for the automatic regulation, control, and monitoring of the building's mechanical and electrical subsystems, such as heating, ventilation, air conditioning (HVAC), lighting, power systems, and security systems. These technical processes are primarily intended to maintain predefined parameters (or set points) and the control of their functionality. BMS employs smart metering and advanced visualization tools to provide real-time monitoring and continuously gather the data on what is taking place in a building and how its equipment is operating and feeding them into a control system to improve energy efficiency. So, the collected data can be used to identify additional opportunities for improvements. Smart homes allow homeowners to control appliances, lights, and other devices remotely using a smartphone through an internet connection.

Smart home technology provides homeowners with convenience and cost savings. A smart device or appliance includes the intelligence and communications to enable automatic or remote control based on user preferences or external signals. Energy monitoring systems (HEMS) present useful information on energy usage directly to the consumer’s devices, allowing them to change their behavior as well as save money in the long run. HEMS also offer homeowners more options than smart meter-to-smart appliance connections, e.g., a sophisticated level of preprogrammed preferences in terms of turning on some appliances based on the amount of the energy consumed within a day, week, or month. Energy monitoring software aims to provide users with information about their consumption patterns by gathering and analyzing relevant data (electricity, heat, gas, water, etc.) using counters or sub-counters present on-site or in the building. This shows users how much energy they are using and how it is used at any time of the day.

Smart Sustainable Waste Management: To achieve far more resource-efficient use of waste that has minimal impacts on the environment requires developing and implementing a number of measures and solutions as part of smart sustainable waste management. Based on the concept of closed eco-cycles, this substrategy encompasses such components as convenient waste collecting system, vacuum waste chutes, food waste disposers, wastewater and sewage treatment system, biological waste separation procedures, and biogas digesters. This strategy encompasses the following substrategies:

- Convenient and smart waste collecting system
- Vacuum waste chutes
- Food waste disposers
- Biogas digesters
- Wastewater and sewage treatment system
- Biological waste separation procedures

Smart waste collection systems are becoming more and more wide-spread, and many cities across the globe are already implementing this solution in the city management programs. Typically, smart management of waste collection involves adopting data-driven resolutions intended to improve the efficiency of the city management, especially in relation to the city districts with no vacuum waste chutes systems.

Smart Environmental Control and Monitoring: Air pollutants as atmospheric substances—especially anthropogenic—have negative impacts on the environment, as well as pose a high environmental risk to human health, so too is noise pollution, both direct and indirect. Noise pollution denotes harmful outdoor sound with road traffic being the major contributor. The demand for the smart systems that monitor the quality of the environment has increased due to the elevation of pollutants in the atmosphere. The rapid urbanization of the world leads to the environmental degradation of the air. Nonetheless, new and emerging technologies allow a real-time tracking capability of the different substances spread in the air, as well as applying preventive measures in a timely manner. Air pollution is due to several gases and dust, such as particulate matter (PM 2.5 and PM 10), Ozone (O3), Nitrogen Dioxide (NO2), Sulphur Dioxide (SO2), Carbon Monoxide (CO), and Carbon Dioxide (CO2). Because air pollution and Greenhouse Gases (GHG) emissions are often released from the same sources, curbing GHG emissions in an effort to slow climate change also reduces air pollutants, such as PM 2.5. Reducing these co-emitted air pollutants improves air quality and benefits human health. GHG emissions are mostly associated with energy and transport sectors. Therefore, one of the significant objectives of the data-driven smart sustainable city of the future is to achieve a healthy and hyper-connected city with limited GHG emissions where urban planning, the environment, and ICT infrastructures are fully integrated and characterized by productive neighborhoods. The focus should be on the impacts of energy consumption on the environment and on control over transport flows and their effects on the noise level.

Smart Urban Metabolism: Urban metabolism as a model is used to facilitate the description and analysis of the flows of the materials and energy in the city and their relationship with its infrastructure and activities. It refers to the total sum of the technical and socio-economic processes that occur in the city, resulting in the production of energy that enables it to grow and evolve, and the elimination of waste. As such, it serves to maintain the functional and evolutionary states of the city as a socio-technical organism. Looking at the data-driven smart sustainable city of the future through a metabolic lens, a framework through which to successfully model the flows of its systems becomes of high importance and interest. This helps to understand the relationship between human activities and the natural environment by studying the interactions of human systems and natural systems. Indeed, urban metabolism provides a platform through which the implications of the different dimensions of sustainability can be considered.

Underlying the data-driven smart sustainable city of the future as an integrated model of urbanism is the idea of relating the underlying metabolism structure to its operational functioning and planning through control, management, optimization, and enhancement. These technical processes should be based on powerful new forms of simulation models and optimization methods fashioned by urban intelligence and planning functions. Especially, the pragmatic framework for urban metabolism used by systems scientists for promoting the concept of urban sustainability has a number of limitations that need to be overcome, including high data and resource requirement, lack of follow-up and evaluation of the evolution of the city's metabolism, difficulties in identifying cause-and-effect relationships of the metabolic flows, and lack of data on energy and material flows. Smart urban metabolism uses advanced data analytics techniques to assess and sustain the required level of sustainability of the data-driven smart sustainable city of the future by computing the ecological footprint and then identifying and suggesting alternative routes of development to reduce it. This relates to the concepts of ecosystem services, urban technical systems, and sustainability principles, as well as to the distribution of functions and population in the city

Smart Street Lighting: The city-wide street lighting system provides tremendous opportunities for modern cities to collect huge amounts of data from urban environments and to transfer them to special centers for their subsequent processing and analysis for enhancing decision making associated with numerous uses and applications. This can be used to make urban living more environmentally sustainable and to enhance the quality of life for citizens. Street lighting is one of the most interesting pathway to using and exploiting the IoT and big data analytics in future cities. Thus, it can be expanded beyond what is originally used for.

Smart Urban Infrastructure Management: Advanced ICT will be focussed on defining critical problems and events that might emerge rapidly and unexpectedly across the city. Analysing and identifying such problems and events is of great importance to urban sustainability and resilience. The smart management of the essential urban infrastructure involves monitoring and controlling its structural conditions in terms of potential changes that can increase risks and hazards as well as compromise safety and quality. In this context, data-driven smart technologies and solutions tend to be mostly justified by the high significance of the natural resources such infrastructure utilizes or involves in its operation.

5.3.3. Social Infrastructure

Social infrastructure is the development and maintenance of the basic facilities combined that are necessary for human development. It is a subset of the infrastructure domain and typically includes assets that accommodate social services. These are provided by a city government, either through the public sector (or related entities) or the financing of private provision of services. Modern cities are facing a number of major transformations in several social areas. And due to these challenges, the public sector is facing huge demands in many areas of its responsibility, such as environmental protection, healthcare, safety, and so forth. Therefore, a significant part of new digital technologies, innovative solutions, interactive platforms, and diverse forms of public-private cooperation have become of critical importance to overcome the social challenges and to bring about the needed transformations in a number of social domains that sustainable cities and smart cities are confronting or facing. This is at the core of the assets of the social infrastructure of the data-driven smart sustainable city of the future, particularly in relation to citizen participation, public safety, healthcare, and education and training. Other assets are part of the built infrastructure, the essential urban infrastructure, and the technological infrastructure, such as facilities, community support, housing, sewerage, water and wastewater treatment, transport, public space, recreation, and so forth. In a wider sense, the data-driven smart sustainable city of the future also has a variety of sustainable development institutions and competence centers whose mandate is improving social, economic, and environmental aspects. The role of these institutions and centers lies in maintaining the planning, development, and governance of the city as a data-driven smart sustainable entity in the future. The social infrastructure strategy focuses on the following substrategies:

- Smart citizens: participation and consultation
- Smart public safety
- Smart healthcare

Smart Citizen: Participation and Consultation: The social infrastructure is about people. Therefore, the involvement of citizens in the management and planning of the data-driven smart sustainable city of the future using information systems is crucial to progress towards its ultimate goal. Such involvement is associated with the adoption of the most important resolutions related to living, which intend to improve the level of satisfaction and increase the level of confidence and trust among citizens in the city administration. The strategy “participation and consultation” aims to stimulate citizens' interest in taking part in the planning and development of the city. Research, knowledge development, and experience feedback are important preconditions for solving complex challenges. The major intellectual challenge to resolve in developing the data-driven smart sustainable city of the future that will benefit the quality of life for all of its citizens lies in embracing the idea that the data-driven technologies developed are the same technologies applied to study the processes of their implementation and impact on society. In this context, the participation of citizens in formulating policies will be very different from the past when the future used to be dictated by top-down decisions. Digital changes can arise from bottom-up actions thanks to the right platforms through which citizens can transform the city they belong to or where they live. This fundamental difference will be enabled by the equally powerful science that big data technologies will unleash. One of the key scientific challenges for the data-driven smart sustainable city of the future that relates to new technologies for communication and dissemination is developing those technologies that ensure widespread participation as well as ensure equity, fairness, and the quality of city life.

Smart Public Safety: It is highly important to develop a much deeper and more informed understanding of the risks, threats, and hazards surrounding the city. This requires a new set of data-driven technologies and collective decision-making processes. Data-driven approaches to urbanism allows to understanding the city as strongly interlinked and coupled systems that generates unexpected and surprising dynamics. Emerging technologies are increasingly changing the nature of such dynamics by predicting them on multiple scales in terms of the properties and processes that stimulate change within the city system, thereby outsmarting it.

Smart Healthcare: One of the key areas targeted by technological advancements and innovations is human health. Medical systems and healthcare services are at the core of data-centric applications. Healthcare management is one of the areas where the highest level of technology development and adoption is observed. The use of data analytics and personal wearable devices in medicine for the diagnosis and treatment of patients is one of the most promising areas of applied data-driven solutions in modern cities. Therefore, the focus should be on the digitalization of medical services to enhance the quality of healthcare provided to all citizens and thus their well-being, as well as to upraise the effectiveness and efficiency of health system management. This entails using advanced tools, powerful computational processes, and innovative systems, such as embedded sensors and actuators, database system integration, management and monitoring software, simulation models, and decision support systems.

5.3.4. Technological Infrastructure

Generally, an ICT infrastructure includes hardware, software, networking, data storage, as well as an operating system. These are used to deliver applied solutions to the different stakeholders of the city. The ICT infrastructure of the data-driven smart sustainable city of the future must be able to integrate numerous application domains for sustainability across various spheres of its administration. Vital elements in this regard are the IoT, big data analytics, and artificial intelligence. These are to be used and integrated in more innovative ways to solve the problems related to the city management.

The ICT infrastructure can be deployed within the city's own facilities or within cloud computing. The ICT infrastructure strategy includes the following substrategies:

- Sensor infrastructure and digital network for data transfer
- IT architecture layers
- Data sources and open data

The competencies associated with the ICT infrastructure pertain to the process of big data analytics in terms of generating, processing, analyzing, and visualizing data for enhancing decision making across the various domains of the city (transport, traffic, energy, environment, healthcare, public safety, etc.). They depend on the scale and quality of the instrumentation, datafication, and computation dimensions of the city. This in turn determines the nature and range of the solutions provided to optimize, enhance, and maintain the performance of the city with regard to sustainability. Digital instrumentation produces huge amount of data, which are transformed into datasets and thus become easily conjoined and shared and highly appropriate for handling. These datasets allow real-time analysis of the different aspects of urbanity to generate deep insights that can be used in decision-making processes and in developing simulation models for managing, planning, and designing more sustainable cities. The essence of digital instrumentation lies in coordinating and integrating technologies (and hence the strategies of sustainable cities and the solutions of smart cities) that have clear synergies in their implementation within development planning and operational management. This opens up and enables realizing many new opportunities in the context of sustainability.

The ICT infrastructure for the data-driven smart sustainable city of the future comprises a collection of smart solutions for various spheres of its administration. It includes novel applications and services for city agencies and departments to serve different stakeholders, and demonstrates the innovative use and integration of the IoT, big data analytics, and artificial intelligence to solve problems within the aforementioned domains of urban life.

Data sources characterize the availability of the actually used and potentially to be used sources of data. Based on the analysis of these data, the data-driven smart sustainable city of the future will be able to make countless and support complex decisions pertaining to planning, design, and operational functioning. However, some data are open and thus accessible to the public for use, while other data are confidential and thus pose privacy issues. Also, some data are available virtually for free, while other data require effort to obtain. Still not all the data needed for the development and implementation of applied data-driven solutions for sustainability exist.

The ICT infrastructure is associated with urban computing and intelligence and the underlying core enabling and driving technologies, including the recent advances in many areas to cope with the challenges in real-world settings, notably:

- Horizontal information platforms and operations systems
- Hybrid systems bridging the physical and digital world
- Urban ubiquitous and intelligent sensor infrastructure
- Smart network infrastructure
- Big data infrastructure for urban analytics
- Real-time data processing and analysis
- Heterogeneous data analytics
- Data mining and knowledge discovery processes
- Artificial intelligence models
- Intelligent energy management for urban sensing and cloud computing
- Urban environment monitoring, analytics, and prediction
- Cloud of Things for smart environment
- Urban visualization methods
- Security and privacy mechanisms

5.3.5. Institutional Transformations

To support the aforementioned infrastructural changes requires major institutional transformations. Drastic shifts to socio–technological regimes—transforming technological regimes for sustainable urban development—“entail concomitantly radical changes to the socio–technical landscape of politics, institutions, the economy, and social values” (Smith 2003, p. 131). Socio–technological regimes—i.e., “interconnected systems of artifacts, institutions, rules, and norms” (Berkhout, Smith and Stirling 2003, p. 3)—are to be brought about by the actions and networks of actors within civic institutions in the ambit of the data-driven smart sustainable city of the future. Generally, institutional transformation denotes profound changes within institutions in the basic values and beliefs that are dominant, as well as in the rules and regulations that lead to certain outcomes. As characteristics of social aggregate, institutions denote the actions, rules, regulations, and social structures and practices that persist over time, and as such, they facilitate the coordination between a range of actors and networks, mediating what govern those behaviors that are deemed of importance for society to make actual progress towards achieving the goals of sustainability.

Supporting the Balancing of the Three Goals of Sustainability: It is crucially important to ensure that the institutional practices and competences related to the data-driven smart sustainable city of the future support the balancing of the environmental, economic, and social goals of sustainability (Figure 5.2). This implies that concrete and distinct actions and measures should be in place as part of a coordinated framework to make the most of the opportunities offered by sustainable development and enabled by technological development. The core institutional practices and competences needed in this regard are presented in Table 5.7 in the form of actions and measures, organized in accordance with the three dimensions of sustainability.

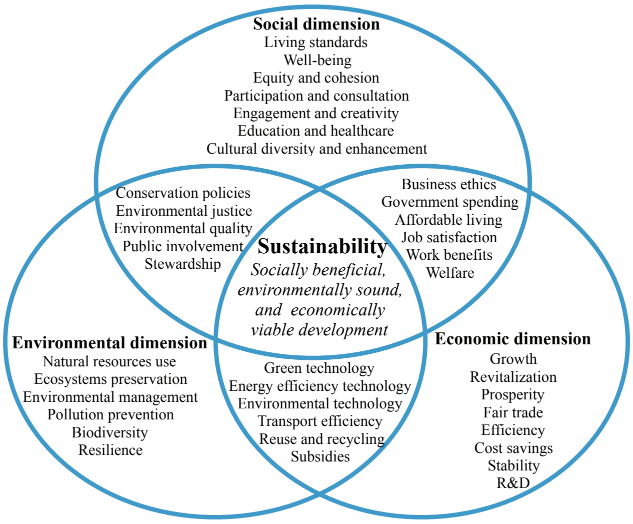

Figure 5.2: A framework for balancing the goals of sustainability

Sustainability	Institutional Practices and Competences
Environmental Dimension	• Make green structure plans that map the city's green resources by assessing their natural and recreational qualities • Use green structure plans as a means to enhance and integrate the available knowledge of the green structure and create the opportunity to gain a coherent view of its totality, as well as to focus attention on the city's merits and shortcomings in regard to green structure preservation • Introduce balancing principles to compensate for any potential loss of natural and agricultural land with a new or reinforced land (e.g., recreational land), so the final result is more valuable • Establish a research center for environmental sustainability • Establish an innovation center for green energy technology • Transform the innovation center into an international meeting place where the city, the business community, and the research community work collaboratively to profile and demonstrate know–how in green energy technology • Establish a research and innovation center for zero emission neighbourhoods • Establish a living lab for zero-emission/net-zero energy buildings as a multipurpose experimental facility to study various technologies and design strategies in a real-world living environment • Establish a research and innovation center for green, passive, and low energy buildings • Support green energy technology innovation projects through funding schemes, advocating the adoption of environmentally friendly products and services, organizing symposiums on environmental innovations, encouraging local environmental programs, and devising comprehensive environmental plans • Create arenas where industry experts, businesses, politicians, and citizens meet to discuss environmental problems and potential solutions

Sustainability	Institutional Practices and Competences
Economic Dimension	• Promote regional collaboration to enhance business development • Make detailed regular plans for business development where the economic goals of sustainability are coupled with the targeted measures. This relates to the balanced scorecard, a strategic management performance metric used to measure and provide feedback to organizations by identifying and improving various internal business functions and their external outcomes • Make strategic business development plans to guide business and tourism development • Expand the tourism industry and boost the regional business links • Use physical planning to adapt the prioritized areas for development to business development • Create arenas where politicians, business actors, and public servants meet to discuss topical questions and issues • Support collaboration and networking with business actors to enhance knowledge and information sharing • Develop higher educational programs that integrate education and research into business development • Intensify collaboration between businesses, educational institutions, and research centers • Inspire and stimulate local entrepreneurship by providing financial support and counselling and by organizing contests between, and offering awards to, young entrepreneurs and innovators • Create various resources to support small and medium-sized enterprises • Establish a research center for innovation, entrepreneurship, and learning • Create R&D projects in light of new city development projects in the medium and long term based on partnerships between government, academia, and industry • Transform new successful sustainable urban development projects into sites that attract new investments, ventures, study visits, further development initiatives, and international interests • Ensure collaboration on and alignment with a shared vision of sustainability among companies, organizations, and institutions with different interests and goals

Sustainability	Institutional Practices and Competences
Social Dimension	• Make public health plans • Develop procedures that secure a linkage between urban planning and public health goals through initiatives to provide access to green and recreational areas, as well as arrangements to improve cycling and walking, thereby enhancing the opportunity to engage people in physical activity • Ensure that the social sustainability plan plays a prominent role in local policy-making, and constitutes the basis for political debate where solutions to the challenges and issues addressed are sought • Ensure that plans rest on statistics, indicators, and qualitative data as the basis of knowledge for political decisions • Make plans on the basis of the areas for improvement identified, and discuss and monitor them on an annual basis. The monitoring to be employed should include a number of issues, such as the number of newly built dwellings, the assortment of dwellings, the affordability of housing, the safety of public spaces, the ability to enhance the quality of life in the city's socio-economically weak and vulnerable areas, the ability to improve the air quality and reduce the noise level, the protection of green and natural areas, and so on • Develop strategic guidelines for social justice, social inclusion, social cohesion, and social capital so that they can be converted into concrete projects and programs • Establish a research and innovation center for social sustainability • Establish a research and innovation center for the IoT and people to study how the citizenry can get the most out of the IoT as a socially disruptive technology with respect to transportation, accessibility, energy, home automation, living, health, learning, and so on in terms of services • Establish a research center for ICT for sustainability aiming to contribute to changes in social institutions, social behaviors, social relations, and social perceptions in a sustainable direction • Establish a research center for sustainable development to contribute to the development of a sustainable society. This contribution includes the shift towards sustainable technical and social systems that meet human needs, such as food, housing, transportation, communication, and recreation • Create a participatory democracy platform that allows citizens to see and discuss proposals put forward by the city government, and submit their own. Such platform is used to create the city's government agenda, with proposals coming directly from the participating citizens • Create a city council that allows the provision of services by public agencies remotely and mobile kiosks, where one can receive various certificates, publish a complaint, get necessary information, and so on. This is to improve the convenience of public services received by citizens • Support and strengthen the technologies that ensure widespread citizen participation by security measures and privacy mechanisms. These should be at the core of urban policy and governance practices associated with the design, development, and implementation of interactive platforms. • Develop and implement advanced technologies that offer the prospect of ending the digital divide, provided that they do not open up other kinds of divides. It is important to explore how new forms of regulation at the level of urban planning, transport planning, economic development, and community development can be improved using future and emerging technologies • Establish a number of digital literacy programs and investigate the reasons behind the digital exclusion of minorities and vulnerable groups, with the overall aim of having everyone online, or with the aspiration to be online by 2050. • Develop a unified medical information and analytical system, combining such services as communication center, electronic registry, electronic health record, electronic prescription, disability certificates, laboratory services, and personalized accounts. • Establish center for social innovation and entrepreneurship to create knowledge and ideas for environmental and social change that will be of relevance to the challenges that the city faces through research, education, and experiential learning. This is important to strengthen the capacity of individuals and organizations to develop innovative solutions to complex problems.

Table 5.7 The core institutional practices for balancing the three goals of sustainability

Introducing Modern Technology and Adopting Applied Solutions in the City Management: The technical and institutional competences pertaining to the data-driven smart sustainable city of the future reflects the degree of its readiness to introduce data-driven technology in its management as well as the degree of the implementation of applied data-driven solutions developed for its management. They are briefly described next, along with their key functions.

Horizontal information platforms: Both the data infrastructure and operating system for the city constitute what is called horizontal information platforms, a key competence for performing the core functions of big data analytics. Functionally compatible horizontal information platforms allow the creation of a united ecosystem for the city. They explicitly link together multiple urban technologies and solutions to enable greater coordination of the city systems and domains (Table 5.8):

- Providing open platforms connecting all the sensors installed in the city and the obtained sensed data Aggregating and standardizing the flows of functional and territorial data from municipal sources, the systems of state control (mobility, energy, noise level, pollution level, etc.), business environment, and other state agencies (hospitals, cultural institutions, universities, schools, etc.), as well as from various detectors and cameras for their subsequent integrated analysis and visualization in 3D format
- Solving the problems of data disconnection in the city through the open operating system integrating and processing the information generated by the city
- Reworking and repackaging the collected data for daily consumption by different stakeholders
- Allowing the city authorities and third party users to gain access to the received data in a more structured and convenient manner for software development
- Providing comprehensive solutions to complex urban problems by integrating the self-contained and unconnected technological solutions and information systems used in the different functional departments of the city
- Improving the efficiency and performance of implemented applied technological solutions
- Allowing the city authorities and other users to take decisions on the optimization of the city activities in the short, medium, and long term

Table 5.8 The key functions of horizontal information systems

Operations centers and dashboards: The city systems and infrastructures will become much more tightly integrated and interconnected as manifested in what is called operations centers and dashboards. These draw together and interlink the data generated by the city complex to provide an integrated view and synoptic intelligence of the city (Table 5.9). The new digital technologies embedded and networked in urban environments will transfer the collected data to a number of control and management systems that can respond in real time to data flows.

- Using visualization sites to help both expert and no-expert users interpret and analyze information, and to allow citizens to monitor the city for themselves and for their own ends
- Employing integrated, real-time data to track the performance of the city and to communicate the live feeds of real-time information to citizens with respect to a number of areas
- Enabling automated systems to respond to citywide events by making immediate decisions pertaining to various urban domains
- Overcoming urban challenges, keeping citizens up-to-date, and developing applications based on the standardized and published forms of open data
- Creating innovative platforms, promoting big data use and application, introducing data-driven technologies, and providing expert assistance

Table 5.9 The key functions of operations centers and dashboards

Strategic planning and policy office: The strategic planning and policy office as an analytical center is key to the management of the city development projects and programs pertaining to the implementation and integration of the compact, ecological, and technological aspects of the landscape of the city, particularly in relation the objectives and targets of sustainable development (Table 5.10).

• Promoting smart approaches through planning systems—making extensive use of data to guide urban planning and design and to encourage developers to deploy digital infrastructure to future proof new developments • Analyzing population displacement and movement data for the strategic planning of city infrastructures, districts, and streets, thereby taking into account the emerging demands from the population • Integrating information on the expectations/uses of the residents of the city districts in the construction of scenarios in response to the need for renewal, redevelopment, and development projects • Developing master and comprehensive plans based on the analysis of the city data • Integrating technology solutions and urban design solutions when developing urban plans and urban development projects • Using a one-stop data analytic hub to bring and weave together data from a variety of city agencies and departments in order to regulate and govern the city and to solve related issues • Collating and analyzing data from a variety of city agencies and departments to enable the city authorities to make decisions more effectively in the fight against crime and on the provision of public safety and quality of life of the city residents • Prioritizing, based on data analysis, the development of the municipal system and ways to improve the efficiency and effectiveness in the provision of urban services, enforcement of laws, as well as the transparency of the city authorities. Among the primary directions of the initiatives to deal with in this regard are: - Support of the city's functions by communication with other city agencies, e.g., adoption of resolutions in the form of models based on data analysis - Data transfer by establishing a platform for exchange of data among various departments, combining data from different sources of various agencies and third party organisations. This can occur through cooperating with the ICT department and the operations centers of the city - Creation of open data portal to be available to anyone interested • Developing and implementing strategies for technological development in the city • Addressing issues of city-wide coordination and cooperation in the field of technologies, playing a bridging role, and advising various city agencies and departments on technological innovations

Table 5.10 The key functions of strategic planning and policy office

Innovation and research centers: The main function of innovation and research centers is to develop, test, and implement new solutions for the different areas of sustainability. Accordingly, they involve building, sharing, and continuously enhancing practical knowledge in response to the goals, strategies, policies, and visions of the city (Table 5.11).

• Creating multidisciplinary teams based on practical know how, long–standing experience, international expertise, and access to global networks • Enabling interaction and promoting cooperation between scholars, researchers, industry experts, business professionals, and thought leaders to enhance research opportunities, academic excellence, real-world problem solving, and knowledge creation and dissemination • Providing the ground for developing and testing innovative technological solutions for urban management • Featuring the latest developments in technologies and solutions and demonstrating how they are applied in real-world settings • Developing urban intelligence functions for improving and optimizing city operations, functions, services. designs, and strategies • Understanding, enhancing, and applying the leading city practices • Integrating resources and expertise for the benefits of the city through collective intelligence • Managing, analyzing and visualizing different kinds of projects • Supporting the city authorities in visioning, strategizing, and implementing sustainable development as a set of objectives and targets

Table 5.11 The key functions of innovation and research centers

Educational centers and training programs: The educational centers and training programs are associated with the creation and accumulation of knowledge and expertise in the areas of urban science, urban informatics, data science, computer science, data-intensive science, and big data analytics and their integration into interdisciplinary fields in relevance to sustainable urban development (Table 5.12). These disciplines are heavily applied fields where the programs offered by the educational institutions should be adequate for enabling the data scientists, experts, and analysts to perform their tasks. The intention is to provide the city with the competences needed to successfully implement the applied technology solutions to improve and advance sustainability.

- Developing educational programs at the intersection of big data analytics, sustainable development, and urban planning and development
- Providing specialized academic programs within urban analytics, urban computing, urban intelligence, and data-driven sustainable urbanism
- Offering a large number of educational programs with data science and analytics discipline
- Introducing data-driven technologies for city operational management and city development planning
- Implementing initiatives for developing competencies in a number of data science and analytics areas in relation to urban sustainability by conducting seminars and providing trainings to improve the level of the applied technological knowledge in this regard

Table 5.12 The key functions of educational centers and training programs

Competence centers: It is important to establish various competence centers as multidisciplinary and multi-stakeholder research and demonstration arena. These centers should address newer subject areas, where efforts should often be conducted in joint projects with businesses and various societal bodies. As autonomous units, they should maintain close connections with industry and act as liaison offices between the hosting universities in the city and other universities in the country. Competence centers should be created in cooperation with all stakeholders of the quadruple helix at the national level, a solution that needs generous support from the government as well as expertise within the various areas of sustainability and technology. Among the competence centers to establish in relevance to the different areas of sustainability are shown in Table 5.13.

- Center for sustainable built environment
- Center for construction efficiency and sustainability
- Center for traffic management research
- Center for transport management research
- Center for integrated sustainable transportation
- Center for smart grid and energy storage
- Center for integrated renewable solutions
- Center for hybrid and electric vehicles
- Center for smart healthcare research: medical systems and services

Table 5.13 Competence centers for sustainability

6. Discussion

This chapter provides a discussion of the research questions (RQ1-RQ8) and the research contributions (C1-C7). Specifically, this chapter revisits the research questions stated in Section 1.4 and shows how these have been answered. This is followed by a similar treatment of each of the research contributions in terms of how the futures study has progressed and the key new understanding that emerged as a result of studying the research problem. Finally, this chapter provides some relevant insights and risks related to the applied methodological framework.

6.1. Research Questions

Table 6.1 provides a mapping between the research questions and the research publication associated with the PhD study. Each research question is discussed separately below.

Research Questions	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13
RQ1	X	X											
RQ2			X										
RQ3				X									
RQ4					X	X	X	X	X				
RQ5										X			
RQ6										X			
RQ7													X
RQ8											X	X	X

Table 6.1: Mapping between research questions and research publications

RQ1: What are the problems, issues, and challenges related to sustainable cities, and how can they be addressed and overcome based on the new technologies offered by smart cities of the future?

RQ1 is concerned with the problematicity surrounding sustainable cities and how to deal with it. This problematicity relates to the development planning approaches and operational management mechanisms related to compact cities and eco-cities as the most advocated models of sustainable urban form. To tackle this problematicity, as compounded by the negative consequences of urbanization, sustainable cities need to embrace and leverage what smart cities of the future have to offer in terms of advanced technologies and innovative solutions. Work conducted for addressing RQ1 is presented in P1 and P2.

The aim of RQ1 is to identify the key problems, issues, and challenges related to sustainable cities as well as smart cities by evaluating and comparing them in the context of sustainability, with a particular emphasis on the former in connection to our conceptualization of smart sustainable cities. In addition, RQ1 intends to highlight the potentials and opportunities enabled by data-driven technologies and solutions for tackling the problems of sustainability and urbanization. The identified problems, issues, and challenges related to sustainable cities helped to formulate the problem domain of the PhD study. Moreover, they largely relate to how sustainable cities should be monitored, understood, analyzed, planned, designed, and managed in order to improve and advance their contribution to sustainability. The need for developing and applying more innovative solutions and sophisticated approaches to optimize, enhance, and maintain the performance of sustainable cities also implies mitigating the extreme fragmentation of sustainable cities and smart cities and the weak connection between them, both at the technical and policy levels. Answering RQ1 provided the foundation for the PhD study. It also justifies the further investigation of sustainable cities to find out whether any progress has been made towards urban sustainability (P6 and P7), as well as the further investigation of smart cities to find out the extent to which these incorporate the goals of sustainability in their development strategics, and which of these goals tend to be prioritized in development practices (P8 and P9). RQ1 relates to C1 and C2.

RQ2: What is the status of the current model of urbanism and what are the dominating trends and expected developments related to the future model of urbanism?

RQ2 was foundational for the futures study and preparatory to the backcasting process, setting the futures research in proper perspective. The aim of RQ2 is to assess the current situation related to sustainable cities and to describe and analyze the dominating trends and expected developments pertaining to smart sustainable cities, with a particular emphasis on big data science and analytics. Addressed by means of P3, RQ2 established the link between the problems, issues, and challenges associated with sustainable cities and the potential solutions offered by smart cities of the future on the basis of the IoT and big data technologies. Additionally, RQ2 sketches the long-term objectives and targets that are to be used to generate the vision of the future (RQ3), and that are to be refined based on the theoretical and practical knowledge gained from the four case studies conducted (P6, P7, P8, and P9). The purpose of RQ2 is to provide the evaluation needed for grounding the future vision in realism. RQ2 relates to C3.

RQ3: How does the future vision look like and how is it different from the current model of urbanism?

The aim of RQ3 is to generate a vision for a desirable future based on the outcome of P3. This means putting the current circumstances and capabilities at the center of attention in terms of both the dominating trends and expected developments related to the future model of urbanism as well as the status of the current model of urbanism. Further, however, RQ3 addresses several questions involving the requirements of the future vision, how the future vision is different from the current model of urbanism, the rationale for developing the future vision, and which technologies have been used in the future vision. The intent of RQ3 is to imagine and articulate how sustainable cities and smart cities can be combined and integrated on the basis of big data technologies as a future sustainable situation to form a new model of urbanism that can facilitate the transition to sustainability. Concerned with the normative side of backcasting, RQ3 initiates the strategic planning process of backcasting by constructing a vision for a sustainable future, which is to be followed by defining and undertaking a series of concrete actions and measures to reach that specified future. This process is to be entirely based on the outcomes of the four case studies conducted (RQ4) as to its phases. RQ3 is associated with C4.

RQ4: How are the four models of urbanism underlying the future vision practiced and justified with respect to sustainability, and in what ways can they complement each other in that respect?

RQ4 covers the four case studies conducted to underpin and inform the strategic planning process of transformative change towards sustainability and thus the future vision. The aim of RQ4 is to investigate and understand the underlying principles in the real-world phenomena involved in the construction of the future vision. RQ4 is addressed by means of P5, P6, P7, P8, and P9.

P5 focuses on the research methodology to explore the topic of data-driven smart sustainable cities of the future. This novel model of urbanism integrates compact cities, eco-cities, data–driven smart cities, and environmentally data-driven smart sustainable cities. Thus, the aim of RQ4 as related to P5 is to review, discuss, and justify the methodological framework applied in the futures study, which combines several

normative backcasting approaches and descriptive case study design. The backcasting approach is employed to achieve the overall aim of the futures study. The case study approach, which concerns the empirical phase of the futures study, was adopted to examine and compare two of a total of six cases in each of the four case studies conducted
.

RQ4 illuminates the urban phenomena of compact urbanism, ecological urbanism, data-driven smart sustainable urbanism, and environmentally data-driven smart sustainable urbanism as occurring within the ecologically and technologically leading cities in Europe. It does so by means of P6, P7, P8, and P9, which focus on how these models of urbanism are practiced and justified with respect to sustainability, and the ways in which they can relate to each other in that respect. The latter is addressed as part of the result and/or discussion section of the four case studies in relevance to the future vision as representing a new integrated model of urbanism.

Specifically, P6 investigates how the compact city model is practiced and justified in urban planning and development with respect to the three dimensions of sustainability, and whether any progress has been made in this regard. Specifically, it focuses on the prevalent design strategies of the compact city model, the ways in which they mutually complement and beneficially affect one another in regard to producing the expected benefits of sustainability, and the extent to which the compact city model supports the balancing of the three goals of sustainability. P7 investigates how the eco-city model, especially its three sustainability dimensions, is practiced and justified in urban planning and development at the local level. Specifically, it focuses on the core strategies and solutions of the eco-city model, the way in which they mutually complement one another in terms of producing the expected benefits of sustainability, and the extent to which the eco-city supports the integration of the three goals of sustainability. P8 investigates how the emerging data-driven smart city is practiced and justified in terms of the development and implementation of its innovative technologies and solutions for sustainability. P9 investigates the potential and role of data-driven smart solutions in improving and advancing environmental sustainability in the context of smart cities as well as sustainable cities, under what can be labeled "environmentally data-driven smart sustainable cities." P9 also provides an overview of the technical literature on the IoT and big data technologies within the framework of smart sustainable cities.

With reference to the future vision, P6 and P7 focus on the design strategies and environmental technology solutions of the existing models of sustainable cities, whereas P8 and P9 center round the applied data-driven technologies and solutions of the emerging models of smart cities. The intent of RQ4 is threefold. Firstly, it provides the foundational elements of the framework for strategic sustainable urban development planning that is to be developed by answering RQ6 through P10. Secondly, it refines the vision of the future (P10) and thus the broadly defined objectives and targets it is translated to (P11). Thirdly, it underpins and informs the development of the novel model for data-driven smart sustainable cities of the future (P11, P12, and P13). RQ4 is associated with C5.

RQ5: What are the dimensions, strategics, and solutions of the future model of urbanism?

RQ5 is answered by means of P10. The aim of RQ5 is to identify the components underlying the future model of urbanism in terms of its dimensions, strategics, and solutions based on the prevailing models of sustainable urbanism and the emerging models of smart urbanism investigated through the case study research carried out as part of RQ4. The purpose of RQ5 is to summarize the results of four case studies conducted in a tabulated format. And in doing so, it provides the ingredients needed to develop an applied theoretical framework for strategic sustainable urban development planning, which is at the core of RQ6. RQ5 relates to C6.

RQ6: How can these components be integrated into a framework for strategic sustainable urban development planning?

The aim of RQ6 is to develop an applied theoretical framework for strategic sustainable urban development planning based on the outcomes of P6, P7, P8, and P9. RQ6 is answered by means of P10, which specifies and integrates the components underlying the future model of urbanism into a framework that is intended to guide the development of the aggregate model of data-driven smart sustainable cities of the future (RQ8). RQ6 relates to C6.

RQ7: What are the benefits, potentials, and opportunities of the future model of urbanism?

The aim of RQ7 is to identify and distill the key benefits of sustainable cities and the potentials and opportunities of smart cities for boosting these benefits with respect to the three dimensions of sustainability and their balanced integration. The intent is to highlight the added value of the future vision and thus justifies the adoption of the developed model for data-driven smart sustainable cities of the future. RQ7 is answered by means of the first part of P13. Combining the answers to RQ7 and the last part of RQ8, which involves the institutional changes necessary for attaining the future vision, is justified by their interrelationship in regard to the three goals of sustainability and the role of data-based city management in improving the contribution to these goals. In particular, to increase the effects of sustainability through combining the benefits, potentials, and opportunities of the prevailing models of sustainable urbanism and the emerging models of smart urbanism requires parallel institutional transformations. RQ7 is linked to C6.

RQ8: What kind of transformational changes are necessary for attaining the future vision, and what are the relevant strategies and pathways to bring about these transformations?

RQ8 addressees the transformations needed for reaching the future vision as well as the relevant strategies and pathways for bringing about these transformations. The transformations are associated with the built infrastructure, sustainable urban infrastructure, smart urban infrastructure, social infrastructure, and technological infrastructure of the landscape of the data-driven smart sustainable city of the future, as well as the associated institutionalized practices and competences. The strategic pathways entail a series of actions and measures that need to be undertaken in order to attain the overall goal of the future vision and thus meet the broadly defined objectives and targets related to sustainability.

Work related to the treatment of RQ8 is presented in P11, P12, and the second part of P13. P11 aims to develop a novel model for data-driven smart sustainable cities of the future, and in doing so, it offers a strategic planning process of transformative change towards sustainability. P11 constitutes the main contribution to this development process. P12 and the second part of P13 are complementary in this regard. P12 is concerned with the smart energy and smart environment transitions related to the essential urban infrastructure in terms of its smart dimension. P13 addresses the institutional changes necessary for supporting the balancing of the goals of sustainability and for enabling the introduction of data-driven technology and the adoption of applied data-driven solutions in city operational management and development planning. P11, P12, and the second part of P13 provide the actions that meed to be taken and the measures that need to be implemented in order to attain the vision of the future. In light of the above, RQ8 relates mainly to the analytical side of backcasting, that is, the possible ways of linking the goal of the vision of the future that lie far ahead in the future to a set of decisive steps that need to be performed now and designed to achieve the preferred future. RQ8 is associated with C7.

6.2. Research Contributions

While Table 2 provides a mapping between the contributions and their relative treatment in the research publications, Table 4 provides an equivalent mapping between the contributions and the research questions. Each contribution is discussed separately below.

Contributions	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13
C1	X												
C2		X											
C3			X										
C4				X									
C5					X	X	X	X	X				
C6										X			X
C7											X	X	X

Table 6.2: Mapping between contributions and publications

Contributions	RQ1	RQ2	RQ3	RQ4	RQ5	RQ6	RQ7	RQ8
C1	X							
C2	X							
C3		X						
C4			X					
C5				X				
C6					X	X	X	
C7								X

Table 6.3: Mapping between contributions and research questions

The main focus of this research is on how to improve, advance, and maintain the contribution of sustainable cities to the goals of sustainability on the basis of the data-driven technologies and solutions offered by smart cities of the future. To accomplish this, we imagined and articulated a vision for a desired future while grounding it in realism, and then we determined the actions and measures to be undertaken to reach that specified future. The main objective of this research is to build a novel model of urbanism integrating the design strategies and environmental technology solutions of sustainable cities with the applied data-driven technologies and solutions of smart cities for sustainability.

C1: Analysis and evaluation of the state of the art in smart sustainable cities

C1 is associated with the current model of urbanism as well as the future model of urbanism in terms of their analysis and evaluation as approaches to sustainable urban development. The concepts of sustainable cities, smart cities, and smart sustainable cities are multifaceted and compound. Hence, it is crucially important in this research work to gain a broader understanding of these urban phenomena in the context of sustainability. To achieve this, an extensive literature review was performed on the interdisciplinary field of smart sustainable cities. This work describes and discusses a number of concepts, theories, and discourses; identifies many research issues and opportunities; and sheds light on emerging scientific and technological trends as well as future planning practices. It additionally highlights a number of research gaps, mostly questions that have not been answered appropriately or at all by any of the existing research within the field of sustainable cities in terms of their contribution to sustainability when it comes to development planning and operational management, as well as within the emerging field of smart sustainable cities. This gap analysis focuses on the difference between what is known and what should be known, thereby identifying what is missing in the literature, particularly in regard to the relationship between sustainable cities and smart cities. Worth pointing out, moreover, is that the new idea of smart sustainable cities is a gap in itself as it is still evolving as a paradigm of urbanism. It follows that this idea has not been studied from the perspective of combining and integrating the design strategies and environmental technology solutions of sustainable cities and the data-driven technologies and solutions of smart cities.

Numerous research opportunities are available and can be realized in the realm of smart sustainable cities. This integrated model of urbanism is proposed to align the existing problems and solutions identified for future practices within sustainable urban development. Its primary objective is to address and overcome the key issues, problems, and challenges associated with the existing models of sustainable cities—compact cities and eco-cities, with the support of what smart cities have to offer in regard to advanced ICT, notably big data technologies. In light of the existing knowledge on urban sustainability and urban ICT, the applied theoretical inquiry is of high pertinence and importance—given that the research within the field of smart sustainable cities is still in the early stages of its development, and that the subject area draws upon influential and contemporary theories from a number of city-related disciplines that have high integration, fusion, and application potential. Worth noting is that the functions of this literature review, apart from the PhD study, are meant to help to guide the other researchers to establish a rationale for many studies within those areas where the research is lacking or has not been done enough on this topic. The intent of providing the justification to carry other studies is to fill many of the existing knowledge gaps in the flourishing field of smart sustainable cities.

C2: Analysis and evaluation of the state of the art in smart cities of the future

C2 pertains to the future model of urbanism in terms of the analysis and evaluation of its data-driven smart strand. C2 is similar to C1 concerning the approach adopted for the literature review, but with a more focus on big data technologies that can be used to address and solve the problems, issues, and challenges related to sustainable cities within the framework of data-driven smart sustainable cities of the future. Given the relevance of big data technologies to dealing with the problematcity surrounding sustainable cities, it is of importance to further elaborate on and document the potential and role of these innovative technologies in improving and advancing sustainability. Towards this end, a comprehensive state-of-the-art review and synthesis was done on the field of smart cities of the future in the ambit of sustainability and related big data technologies and their novel applications. By the same token, this work describes and discusses a number of concepts, theories, and discourses; identifies many research issues and opportunities; highlights the benefits and potentials of applied technology solutions; shed lights on emerging technological trends and future planning practices; and examines the key challenges and open issues associated with the uses of big data analytics.

Of more relevance to this research work, the identified tremendous opportunities for developing and implementing data-driven applications within smart cities of the future to improve their contribution to the goals of sustainability are intended to be embraced and leveraged by sustainable cities to optimize and enhance their operations, functions, services, designs, strategies, and policies in line with the vision of sustainability, This is justified by the kind of well-informed decisions enabled by the deep insights that can be extracted by the process of big data analysis in the form of applied intelligence. As regards the identified challenges and open issues associated with smart cities of the future, they also apply to sustainable cities. This means that sustainable cities are also required to address and overcome them to achieve a successful implementation of data-driven applications and thus ultimately optimize, enhance, and maintain their performance with respect to their contribution to sustainability.

Furthermore, the review identifies many research gaps within the field of smart cities of the future, particularly in relation to their contribution to sustainability. Accordingly, the functions of this review, apart from the PhD study, are meant to help to guide the other researchers to establish a rationale for many studies within those areas where the research is lacking or has not been done enough on this topic. The intent of providing the justification to carry other studies is to fill many of the existing knowledge gaps in the field of smarter cities.

C3: Assessment of the current situation and trend analysis

C3 is foundational for the futures study and preparatory to the backcasting process, setting the futures research in proper perspective. At the core of the strategic problem orientation phase of the futures study is the assessment of the current situation related to sustainable cities and the analysis of the dominating trends and expected developments related to smart sustainable cities. The focus of the former is on the interrelated problematicities of sustainable cities and the underlying causes, in addition to how the overall problem is defined. In this respect, it is key to establish the link between the problems, issues, and challenges pertaining to sustainable cities and the potential solutions offered by smart cities of the future on the basis of big data technologies. Describing or clarifying the current situation of the socio-technical system to be studied is necessarily present as a step in all backcasting approaches, regardless of their focus and the extent to which they can be adapted to fit the objectives of the researcher. The focus of the latter is on the intertwined dominating and emerging trends and expected developments related to the future model of urbanism. As with all paradigms of urbanism, data–driven smart sustainable cities have emerged and materialized as a result of an amalgam of several trends. These also shape and drive the expansion, success, and evolution of this new paradigm of urbanism. The key identified trends include:

- Global trends: sustainability, ICT, and urbanization
- Academic discourses: sustainable urbanism, compact urbanism, ecological urbanism, smart urbanism, data-driven urbanism, scientific urbanism, and sustainable urban development
- Urbanism paradigms: sustainable cities, smart cities, smart sustainable cities, and data-driven smart sustainable cities
- Computing paradigms: ubiquitous computing, sentient computing, the IoT, big data computing, fog/edge computing, urban computing, and distributed computing
- Scientific paradigms: data–intensive science (data-driven science and empiricism) and big data science
- Technological trends: big data analytics, the IoT sensing, artificial intelligence, datafication, and digitalization

These forms of trends reflect a congeries of global and societal forces behind the continuation of data-driven smart sustainable cities as a set of strategies and pathways for achieving the SDG 11.

The main expected developments identified are believed to be already happening, and include, but are not limited to:

- Instrumentation, computerization, datafication, and computation are routinely pervading the very fabric of sustainable cities.
- Sustainable cities are increasingly dependent upon their data to operate properly—and even to function at all with regard to many domains of city life.
- Sustainable urban practices (planning, design, management, and governance) are becoming highly responsive to a form of data–driven urbanism.
- Sustainable cities are increasingly adopting big data technologies and solutions to improve, advance, and maintain their contribution to the goals of sustainability.
- Sustainable cities and smart cities are becoming more and more connected as approaches and less fragmented as landscapes.
- Smart sustainable cities are gaining strong momentum worldwide as a promising response to the challenges of sustainability and urbanization.

- Data–intensive science as a fourth scientific paradigm is drastically changing how scholarly research and scientific exploration can be done.
- Big data science and analytics is revolutionizing science, advancing knowledge development, creating new discourses, enhancing social practices, catalyzing major shifts, and fostering societal transitions.

In addition, the long-term objectives and targets related to sustainability are outlined with respect to the future model of urbanism. This is of relevance to the generation of the future vision (C4). The targets are specific desired outcomes that support the achievement of the objectives, which in turn define an endpoint of concern and the direction of change that is preferred. The targets and objectives should be—specific, measurable, achievable, relevant, and targeted when adopting the future model of urbanism. They are decided on according to what the data-driven smart sustainable city of the future aspires to achieve, an ambition that can be adapted to existing sustainable cities in their own contexts. The targets and objectives are refined as part of C7 in the light of the new theoretical and practical knowledge gained from carrying out the four case studies (C5).

C4: Construction of the future vision

The future vision constructed in P4 (C4) is grounded in realism based on the outcome of C3. C4 represents the normative side of backcasting, which entails envisaging a vision for a sustainable future where the problems, issues, and challenges related to sustainable cities have been solved by means of the data-driven technologies and solutions offered by smart cities of the future. This in turn means meeting the objectives and targets related to sustainability as specified in P3 and refined in P11. The future vision as representing the novel model for data-driven smart sustainable cities of the future is different from the current model of urbanism (sustainable cities). This is supported by providing the rationale for developing the future vision as an alternative model of urbanism. The arguments, a set of reasons given in support of this model, are distilled from P3. There are many explanations for controlling the concepts and principles underlying the existing models of sustainable cities in the context of sustainability. The same applies to the integration of sustainable cities and smart cities as to what each has to offer as regards sustainability. The intention is to justify the research pursuit of investigating, underpinning, and developing the new model for data-driven smart sustainable cities of the future (C5, C6, and C7).

In addition, the future vision is refined based on the new theoretical and practical knowledge gained from conducting the case study research (C5). In this regard, constructing the future vision entails retaining the best of what we already have that have been successfully enacted in real-world cities, making use of the things that have been demonstrably better in the past, while being selective in adopting the best of what is emerging and promising, making use of the things that will add a whole new dimension to sustainability in terms of harnessing its synergistic effects, balancing its dimensions, and thus boosting its benefits. The future vision revolves around a co-evolution process of sustainability and technology within the domain of urbanism—shaped by the idea of combining and integrating the prevailing paradigms of sustainable urbanism and the emerging paradigms of smart urbanism in terms of their dimensions, strategies, and solutions (C6).

C5: Illumination of the urbanism paradigms underpinning the strategic planning process of backcasting

The whole strategic planning process of transformative change towards sustainability—the constructed future vision, the specified objectives and targets, and the developed strategies and pathways—is grounded in case study research together with creative and visionary ideas. Investigating the identified four models of urbanism is intended to illuminate the phenomena of compact cities, eco-cities, data-driven smart cities, and environmentally data-driven smart sustainable cities. To achieve this objective, a suitable methodological framework is adopted that combines and integrates a set of principles underlying several normative backcasting approaches as well as descriptive case study design. To backcast in this futures research is about combining and integrating the dimensions, strategies, and solutions of sustainable cities and smart cities into a new model of urbanism based on the outcome of the case study research. The backcasting approach applied in the futures study is well-suited for long-term urban problems and urban sustainability solutions due to its normative, goal-oriented, and problem-solving character. It is effective in indicating pathways for sustainability transitions, thereby its role in supporting policymakers and facilitating and guiding their actions with respect to strategic sustainable development.

The case study approach is one of the most effective ways to underpin and increase the feasibility of the future vision due to its ability to facilitate the investigating and understanding of the underlying principles in the real-world urban phenomena underlying the future vision. Moreover, case studies often represent the first toe in the water in new research areas. Carefully studying any unit of a certain universe allows to find out about some general aspects of it, at least a perspective that guides subsequent research. The case study approach is regarded as a tool with which theories and their effects can be illustrated and new ideas can be generated. The purpose of analyzing and evaluating the selected cases is to provide the theoretical and practical foundations necessary for backcasting the phenomenon of data-driven smart sustainable cities of the future. In this respect, it is important first and foremost to define which characteristics of the future state of this phenomenon are meaningful, beneficial, and interesting. This involves both the theoretical underpinnings and emerging practices of urban sustainability that are of relevance and importance as a foundation for the strategic planning process of transformative change towards sustainability. Overall, the methodological contribution relates to the appropriateness of applying theoretical concepts and perspectives developed in other contexts, and whose successful use in the futures study contributes towards providing the interpretation of the four case studies underlying the backcasting process.

The six cases selected from the ecologically and technologically leading cities in Europe are examined, compared, and discussed in more detail in P6, P7, P8, and P9. The focus in these four case studies is on the nature and extent of the contribution of the four models of urbanism identified to the goals of sustainability. Specifically, on the balance and integration of the three dimensions of sustainability with respect to sustainable cities, and on the role and potential of data-driven technologies and solutions in advancing sustainability in regard to smart cities. This is coupled with how each model of urbanism relates to another in the context of sustainability at the technical and policy levels.

Concerning the case study conducted on compact cities (P6), compactness, density, diversity, mixed-land use, sustainable transportation, and green space are the core design strategies used in compact urbanism to support the balancing of the three goals of sustainability. Greening, which is typically characteristic of eco-cities, is contextually linked to the concept of green structure as an institutional setup under which the two cities investigated operate. Moreover, there is a clear synergy between the underlying design strategies in terms of their cooperation to produce combined effects greater than the sum of their separate effects as regards the tripartite value of sustainability. In addition, the compact city model is justified by its ability to contribute to the economic, environmental, and social goals of sustainability. Indeed, compact urbanism is being enhanced with some elements of ecological urbanism and strengthened by new institutionalised practices to support the balancing of the three goals of sustainability, This is due to the fact that the environmental and social goals of sustainability still play second fiddle. In fact, it is of high relevance and importance to integrate the compact city and eco-city models. This is justified by the fact that:

- the compact city needs to enhance its environmental performance;
- the eco-city needs to improve its social performance that indeed is better in the compact city; and
- both contribute differently to economic sustainability, with the former focusing on mixed-land use strategy and the latter on green-tech innovation strategy.

The last two bullet points are discussed in more detail in the case study conducted on eco-cities (P7), where design and technology are found to be the main strategies and solutions for achieving sustainability. Similar to the compact city, there is a clear synergy between the underlying strategies and solutions in terms of their cooperation to produce combined effects greater than the sum of their separate effects with respect to the benefits of sustainability, yet with its environmental dimension clearly dominating over its economic and social dimensions. This is due to the fact that the eco-city emphasizes ecological design, ecological diversity, and passive solar design, as well as environmental management and other key environmentally sound policies. Nevertheless, while the environmental goals remain at the core of planning and the economic and social goals still play second fiddle in ecological urbanism, some attempts have been undertaken to strengthen the influence of the latter goals over urbanism practices based on compactness towards integrating the three dimensions of sustainability.

With respect to the case study research carried out on data-driven smart cities (P8), there is a high level of the development of applied data-driven technologies as well as their implementation in the various spheres of the city administration to optimize and enhance sustainability performance. The high level of the development of data-driven technologies (notably ICT infrastructure and data sources) is associated with the degree of the readiness of the city administration to introduce data-driven technologies in city operational management and development planning. The high level of the implementation of applied data-driven technologies is associated with the degree of the adoption of data-driven solutions in the different spheres of the city administration, including transport, traffic, energy, environment, citizen participation, public safety, and healthcare. In this respect, a number of technical and institutional competences are employed and established to improve and advance the different areas of sustainability, notably horizontal information platforms, operations centers, dashboards, educational institutes and training programs, innovation labs, research centers, and strategic planning and policy offices. This demonstrates the untapped synergistic potential of the integration of innovative solutions and the strategies and technologies of sustainable cities on the basis of the IoT and big data analytics. Indeed, the real challenge for the future lies in moving genuinely past the assumption that there are only two contrasting, mutually exclusive realities. With an ‘either/or’ approach, there will not be much progress in sustainable urban development as the huge challenges facing sustainable cities within many of their administration spheres require an integrated approach.

The need for sustainable cities to embrace and leverage what smart cities have to offer in order to optimize, enhance, and maintain their performance and thus achieve the desired outcomes of sustainability is further demonstrated by the forth case study done on data-driven smart cities and eco-cities—whose combination can be dubbed as environmentally data-driven smart sustainable cities (P9). In this emerging paradigm of urbanism, smart grids, advanced metering infrastructure (AMI), smart buildings, smart environmental monitoring, and smart urban metabolism (SUM) are the main data-driven solutions applied in smart cities and eco-cities combined to improve and advance the goals of environmental sustainability. There is a clear synergy between such solutions in the sense of their cooperation or interaction to produce combined effects greater than the sum of their separate effects—with regard to the environment. While the clear synergy pertaining to the design strategies and sustainable technologies of sustainable cities contributes to the three goals of sustainability, the data-driven technologies and solutions of smart cities are of crucial importance to boost such contribution, particularly at the environmental and social levels. This in turn provides great potential and new opportunities for balancing the goals of sustainability within the framework of data-driven smart sustainable cities of the future.

In sum, up till now, the four models of sustainable urbanism and smart urbanism investigated are weakly connected as approaches and extremely fragmented as landscapes at the technical and policy levels. The compact city and eco-city models of sustainable urbanism, which have been around for over four decades or so, have many overlaps among them in their ideas, concepts, and visions, as well as distinctive concepts and key differences. The overlap is justified by the fact that they both represent the central paradigms of sustainable urbanism. Therefore, they are, to great extent, compatible and not mutually exclusive. As to the data-driven smart city as an emerging paradigm of smart urbanism, it shares the challenges of sustainable development with the two models of sustainable urbanism, with the main difference being that it focuses more on the use and adoption of data-driven technologies and solutions and related technical and institutional competences to overcome these challenges—than on the planning practices and design strategies of urban sustainability. Concerning the environmentally data-driven smart sustainable city model, it emphasizes the dimension of environmental sustainability and employs data-driven technology solutions to reach environmental targets. In this sense, this model combines concepts and ideas from both the eco-city and the data-driven smart city. These two models are increasingly being merged on the basis of the IoT and big data analytics technologies in a bid to overcome the significant challenges posed by climate change in the face of the escalating trend of urbanization. However, while both implement data-driven technology solutions to improve and advance environmental sustainability, they remain significantly divergent with respect to their priorities, visions, policies, strategies, pathways, and goals, thereby the meaningfulness of their integration in the fourth case study.

C6: Development of an applied theoretical framework for strategic sustainable urban development planning

At the core of C6 is to inform and guide the development of the novel model for data-driven smart sustainable cities of the future with respect to the last phase of the strategic planning process of transformative change towards sustainability. This is done by means of the applied theoretical framework for strategic sustainable urban development planning developed on the basis of the outcome of C5. This integrated framework conceptually captures the core components underlying the future model of urbanism in terms of its dimensions, strategies, and solutions as derived from the prevailing paradigms of sustainable urbanism and the emerging paradigms of smart urbanism. As illustrated in the framework in Section 5.3, there are four basic categories and criteria that are used in defining the data-driven smart sustainable city of the future: (1) compact urban strategies, (2) ecological urban strategies, (3) data-driven technologies and solutions for sustainability, and (4) data-oriented technical and institutional competences. These combined result in improving and advancing the contribution of sustainable cities to the environmental, economic, and social dimensions of sustainability through harnessing their synergistic effects and supporting their balanced integration. In other words, the data-driven technologies and solutions are applied in the operational management and development planning of sustainable cities in order to improve and advance their contribution to and balancing of the goals of sustainability.

The proposed framework is of an applied theoretical nature because it represents an integration and fusion of a number of theories from different established and emerging city-related academic and scientific disciplines together with the effects of their application to the built environment on urban living. These theories and disciplines have high application potential in terms of informing and guiding the processes and practices of the future model of urbanism. This relates to the core foundational concepts and principles of data-driven smart sustainable urbanism as an applied domain in terms of its scientific, technological, computational, social, cultural, and political facets. In short, the underlying theories constitute a foundation for actions. Moreover, the futures study with its concern being strategic sustainable urban development planning, its methodology involving investigation and analytical work, and its direction being applied theoretical needs to link to what is happening in the world around us as regards successful practices, knowledge advancement, scientific discoveries, technological innovation, and so on.

Related to C6 is the key benefits of sustainable cities and the key potentials and opportunities of smart cities with respect to the three dimensions of sustainability as distilled from C5. The outcome is intended to highlight the added value of their combination in the ambit of data-driven smart sustainable cities of the future in respect to maximizing the tripartite value of sustainability. It also relates to the future vision as to what it brings and opens up as new circumstances and responses that cannot be offered by the current model of urbanism in the context of sustainability due to its focus on design strategies and environmental technology solutions.

C7: Development of a novel model for data-driven smart sustainable cities of the future

The novel model for data-driven smart sustainable cities of the future is developed in the form of a strategic planning process of transformative change towards sustainability. This process consists of three main phases as detailed in chapter 5: (1) the vision of the future, (2) the objectives and targets of sustainable development, and (3) the strategies and pathways for transformative change. The focus is on the analytical side of backcasting (phase 3), that is, the step of looking back from the desired future to the present to determine the decisive steps on how to attain the future vision. These steps are the next concrete actions and measures to undertake to bring about the transformations necessary for achieving the overall goal of the future vision and thus meeting the long-term objectives and targets related to sustainability. They represent a set of specific recommendations derived from the outcomes of the four case studies to the different stakeholders of the city depending on their role and interests. As regards the transformations, they are associated with the built infrastructure, sustainable urban infrastructure, smart urban infrastructure, social infrastructure, and technological infrastructure of the landscape of the data-driven smart sustainable city of the future, as well as the associated institutionalized practices and competences. With respect to the latter, the emerging data-driven technological changes pertaining to sustainability are reconfiguring the broader socio-technical landscape of politics, policy, and institutions, as well as providing insights to policymakers into pathways for enhancing existing institutionalized practices and competences and developing and establishing new ones. This is necessary for balancing and advancing the goals of sustainability and thus achieving the vision of the future.

At the core of the developed strategies and pathways is the practice-oriented process of designing and developing the data-driven smart sustainable city of the future to bring about the needed change. This relates to the pathway-oriented category of backcasting the futures study is concerned with—the strategic pathways that connect a desirable state of the future to the present. That is to say, linking goals that lie far ahead in the future to some decisive steps that are to be designed and taken now to achieve those goals. This means transforming the landscape of the data-driven smart sustainable city of the future through combining and integrating compact and ecological designs, sustainable technologies, infrastructural developments, and technological infrastructures in line with the overall goal of the future vision. However, setting strict goals in perspective of the pathway-oriented category of backcasting is of less importance compared to action-oriented backcasting, target-oriented backcasting, and participation-oriented backcasting. These are part of future work (see Chapter 7). Overall, the planning process of the strategic pathway-oriented backcasting provides the how of making progress towards achieving the goals of sustainability for those cities that are badging or regenerating themselves as sustainable, or manifestly planning to be or become smart sustainable in the era of big data.

The discussion of the research questions and contributions has demonstrated the complex and evolving nature of the field of data-driven smart sustainable cities. The answers to the questions must accordingly be high-level and general, if not related to a specific context. By considering the contributions as a delivery towards answering the research questions, the research aim is considered as satisfied. It is hoped that the work reported in this thesis will contribute to the foundational blocks of the field.

6.3. Methodological Insights and Risks

The transformative change towards sustainability as a planning process can benefit from being undertaken in a strategic step-by-step manner. When applied in planning towards urban sustainability, backcasting can increase the likelihood of handling the physically, environmentally, socially, and economically complex issues in a systematic and coordinated way, and also to foresee certain changes.

6.3.1. Backcasting

Backcasting is particularly useful when problems at hand are complex, and in this case, it provides the possibility of a more reliable approach of the planning procedure. However, like many planning tools, the outcomes are not necessarily the fault of the tool but more the user of the tool, which trends to apply to all categories of backcasting. The knowledge of the user is therefore essential to achieving tangible results from applying backcasting. Moreover, backcasting as a normative tool and planning journey, involves a number of risks. In terms of normative scenarios, the future vision represents a normative approach to urban sustainability, which is meant to form the foundations of political decisions and policymaking actions. As such, it implies a certain desired view on the world. It also lacks the ability to contend with the uncertainty surrounding sustainability. Another problem with backcasting is the context in which it is used and the timing of its use in regard to uncertainty. The context is to be set by the stakeholders taking part, or defined as part of the planning process. Different context means different results, and one contextual setting—internal and external—may involve different approaches, processes, or a combination of both. Additionally, backcasting potentially presents higher risks when developing strategies and pathways at times of uncertainty, as it is based an ideal direction or a desirable path to pursue. However, while its use is advocated in time of uncertainty, it will ultimately depend on the ability of the user of the tool. Therefore, backcasting has to be used in conjunction with other tools in strategic planning, e.g., forecasting to quantify the consequences of different measures and actions. Further, many different futures are possible, which is typically contingent on the kinds of decisions to be made and the kinds of actions to be taken in the present for reaching the future vision.

In addition, backcasting cannot provide a journey with no obstacles or bends. All journeys have problems that need to be addressed and overcome along the way. Sometimes, it is necessary to go in a different direction or take a diversion to get to the destination. While imagining a desirable future can inspire strategies and actions, the path to success is not always straightforward. Nevertheless, the guiding images of the future coalesce and together steer the trajectory of where to be headed, which is usually based on reacting to current circumstances, knowledge, creativity, and common sense. Regardless, there may be a paradigm shift in science, technology, and policy, which can deflect the city from its ultimate goal, or delay the progress on its journey to reaching the future vision. As a visioning tool, backcasting helps to identify where to go and what it will look like when reaching the destination. In particular, it helps identify in detail a significant number of issues that sustainable cities will have to deal with, the steps it will have to take in preparation for the journey or during the journey, while being realistic as regards their capabilities to undertake the journey. With respect to the latter, for example, costs are expected to increase as a result of active political measures and planning actions to achieve the desired outcome of sustainability, such as the escalating costs of scarce and non-polluted resources, management of toxic waste, use of sustainable materials, implementation of social initiatives, promotion of business development, and financial support of innovation and entrepreneurship. On the whole, while backcasting will not act as a crystal ball for the targeted cities to achieve the desired outcomes of sustainability, it will allow these cities to set a plan in place for their direction towards the goal.

6.3.2. Case Study

The four case studies conducted were useful for illuminating the four urban phenomena, for illustrating the general principles underlying these phenomena, and for generating new ideas and research questions involving the relationships between these phenomena. However, taken separately from the backcasting-oriented futures study, the case studies cannot substitute for carefully controlled correlational studies as they by definition are low in internal validity and external validity. These two concepts reflect whether or not the results of the four case studies are trustworthy and meaningful. Internal validity relates to how well these studies are conducted in terms of their structure, whereas external validity relates to how well the outcomes of these studies are applicable to the real world. Generally, internal validity denotes the approximate truth about inferences regarding cause-effect, or the extent to which a reliable causal relationship between a treatment and an outcome can be established in a study. As regards external validity, it is concerned with whether the results of a study can be generalized to and across other settings. A common limit of case studies is that they do not lend themselves to generalizability. Typical risks include the representativeness of the subjects with respect to the target population in terms of sustainable cities and smart cities as umbrella terms.

Various designs have been proposed for preparing, planning, and conducting case study research. These designs tend to determine how low internal validity is. Internal validity may be relevant in such case study designs as hypothesis-generating, heuristic, and explanatory, though to varying degrees. In this research, descriptive research design was used to describe some characteristics of complex urban phenomena, and did not address questions about why and when these characteristics occurred—no causal relationship. Besides, as the subjects selected for investigation were cases of multifarious phenomena, coupled with the multiplicity of the data collection methods applied, any kind of causal relationship would have not been feasible or achievable.

The case study research represents the empirical basis of the backcasting study. The outcome of the backcasting study cannot be generalized to other settings due to the fact that it is grounded in descriptive case study research. A common limit of case studies is that they do not lend themselves to generalizability. Typical risks include the representativeness of the subjects with respect to the target population. The target population in this context pertains to the comprehensive group of sustainable cities and smart cities with common characteristics that are of relevance to the futures study. However, the first potential risk to external validity is the relationship between the subjects and the population to generalize to. Four of the subjects selected were sustainable cities from Sweden and the remaining two were smart cities from Spain and the UK. This homogeneous population cannot be generalized to other settings. The subjects are in no sense a sample representative—accessible population—of a target population. They are selected merely because they are interesting examples through which the lineaments of the four objects: (1) compact urbanism, (2) ecological urbanism, (3) data-driven smart urbanism, (4) and environmentally data-driven smart sustainable urbanism can be refracted. The selection strategy pursued in the case studies is influential cases—are central to a model or theory (Seawright and Gerring 2014). The second potential risk to external validity is posed by the collection of data. In general, recognizing the importance of external validity, researchers attend to the ways they collect data. With respect to the data acquired from those documents produced by other researchers and organizations as secondary sources, the studies included did involve the risk of the representativeness of the subjects with respect to the target population as well.

7. Conclusions

This chapter provides the conclusion of the thesis and the most important insights gained from this research. It also suggests some avenues for future work in relevance to the strategic planning process of backcasting.

7.1. Conclusive Summary

Sustainable cities are always about citizens. Being data-driven smart about sustainable cities requires to connect directly to the concerns and feelings of people with respect to environmental protection, economic regeneration, and social justice, as well as urban revitalization and attractiveness. Historically, people have always moved to and preferred to live in sustainable cities to improve the quality of their lives and well-being. And smart urbanism is being embraced anew as a strategic move to create sustainable cities that make urban living more sustainable over the long run. Towards this end, sustainable cities have to learn faster and identify strategies and pathways that work. Working with long–term images of the future is meant to stimulate new opportunities to attain the kind of sustainable cities that last thanks to emerging and future data-driven technologies and solutions for sustainability.

This PhD study focuses on how to improve, advance, and maintain the contribution of sustainable cities to the goals of sustainability on the basis of the data-driven technologies and solutions offered by smart cities of the future. To guide the research (backcasting) process, we posed eight research questions (Section 1.4), which were answered in Chapter 4. The (futures) research led to seven contributions (Section 1.6) to the knowledge in the field of smart sustainable urbanism, which were published in thirteen scientific research articles.

The aim of the PhD study was to analyze, investigate, and develop a novel model for data-driven smart sustainable cities of the future. The methodological framework applied to achieve this aim involved literature studies, trend analysis, four case studies, and analytical work, following six steps that we developed and adapted to the objectives of the futures study. Accordingly, we identified the major problems, issues, and challenges related to the current model of urbanism (sustainable cities), as well as the dominating trends and expected developments related to the future model of urbanism (data-driven smart sustainable cities). This was followed by constructing a vision for a desirable future, which was translated into broadly defined long-term objectives and targets in relation to sustainability. Based on the requirements of the future vision, we investigated four models of urbanism. This investigation focused on how compact cities, eco-cities, data-driven smart cities, and environmentally data-driven smart sustainable cities are practiced and justified with respect to sustainability, and in what ways they can relate to each other in that respect. The resulting outcome enabled us to specify the underlying components of the future model of urbanism in terms of its dimensions, strategies, and solutions, develop a framework for strategic sustainable urban development planning, and to identify the benefits, potentials, and opportunities of the future vision. The developed framework was subsequently used to guide the development of the novel model for data-driven smart sustainable cities of the future in the form of a strategic planning process of transformative change towards sustainability. This involved the strategic pathways needed to bring about the transformations necessary for attaining the future vision and thus meeting the long-term objectives and targets related to sustainability. The strategic pathways were a series of actions and measures pertaining to the built infrastructure, sustainable urban infrastructure, smart urban infrastructure, social infrastructure, and technological infrastructure of the landscape of the data-driven smart sustainable city of the future.

This empirically grounded model of urbanism is meant to be specific enough in terms of its components based on the creative integration of the prevailing paradigms of sustainable urbanism and the emerging paradigms of smart urbanism. Its essence lies in providing the needed tools, techniques, methods, systems, platforms, and infrastructures enabled by the core enabling and driving technologies of the IoT and big data analytics for sustainable cities to optimize, enhance, and maintain their performance with respect to the contribution to the goals of sustainability.

The suitability of backcasting for the kind of problems that are associated with sustainable cities in that respect stems from the problem-solving and goal-oriented character of backcasting that is embedded in its process of strategic planning. Backcasting is useful in studying problems that are complex and associated with persisting trends that contribute to the problems' complexity. Moreover, it allows to imagine the impacts of the future vision, which should be highly significant and entail extensive and ambitious improvements and advancements compared to the current trend. The advantage of using this framework lies in its foundation and efficacy with regard to providing insights into and developing pathways for sustainability transitions, as well as in its ability to produce desired outcomes. This is of high relevance and importance to policymakers as to informing strategic plans for achieving the objectives of sustainable development and thus making actual progress towards sustainability. Here, backcasting can be viewed as a process of transformative change in the sense of how sustainable cities can be designed and developed so that they become able to monitor, understand, analyze, and plan their infrastructures more effectively. All in all, the new model of urbanism can be seen as an important arena for sustainability transitions in the era of big data. It offers a clear prospect of instigating a major transformation by synergistically connecting the agendas of urban development, sustainable development, and technological development for a better future.

7.2. Research Implications

The overall outcome of the PhD study is a new model of urbanism integrating the design strategies and environmental technology solutions of sustainable cities with the applied data-driven technology solutions of smart cities for sustainability. There are several implications of this research in terms of how the findings are important for practice, policy, methodology, and future work (addressed separately next).

The first practical contribution of this research is that it helps policymakers and planners to address and overcome the extreme fragmentation of and the weak connection between sustainable cities and smart cities as landscapes and approaches, as well as to adopt a more holistic and integrated perspective when dealing with sustainability thanks to big data analytics. The latter has been, and is still, one of the great conundrums facing sustainable cities when it comes to responding to the challenges of sustainable development. For example, the resulting model provides important tools and insights into integrating compact city and eco-city policies to achieve the desired outcomes of urban sustainability in terms of balancing its dimensions and boosting its benefits. It also consolidates the design strategies and environmental technologies of sustainable cities, as well as strengthen them with the data-driven technologies and solutions of smart cities thanks to urban computing and intelligence. With this integrated set of advanced technologies being able to bridge the gap between unobtrusive and ubiquitous sensing, intelligent computing, cooperative communication, and massive data management and analytics, urban designers and engineers may overcome one of the scientific challenges pertaining to sustainable cities—relating their built infrastructure, urban infrastructure, and social infrastructure to their operational functioning and planning through data-based control, optimization, and management mechanisms. This in turn allow planners to leverage the collective intelligence of sustainable cities in making actual progress towards achieving the goals of sustainability by monitoring, understanding, analyzing, and effectively planning their infrastructure and resources. In fact, the real challenge for the future lies in moving genuinely past the assumption that there are only two contrasting, mutually exclusive realities—sustainable cities and smart cities. An 'either/or' approach will hamper progress towards urban sustainability, as the huge challenges facing sustainable cities in many of their systems and domains require an integrated approach to urbanism. One of the implications of integrating data-driven smart urbanism and sustainable urbanism is that the systems and domains of sustainable cities will become much more tightly interlinked and coordinated respectively.

A second important implication derives from the uniqueness of the holistic knowledge compiled, transformed, enhanced, and expanded in the form of a strategic planning process of transformative change towards sustainability that can be used to guide sustainability transitions in the era of big data. Indeed, the proposed model of urbanism is intended to be presented to the world, something to be replicated in major cities or adopted in new cities. Especially, it serves as a strategic sustainable urban development framework for facilitating progress towards achieving the long-term goals of sustainability for those cities that are badging or regenerating themselves as sustainable, or manifestly planning to be or become smart sustainable in the era of big data. As such, it has great potential to boost new forms of policy analysis and to enhance institutionalized planning practices in the context of sustainability. In addition, it can be used for benchmarking, assessing, and ranking sustainable cities in terms of the extent to which these embrace smartness to improve their performance with respect to sustainability.

A third important practical contribution of this research relates to the enabling role and innovative potential of urban computing and intelligence in enhancing strategic planning and enabling joined-up planning. The latter form will be adopted using urban intelligence functions as an advanced form of decision support, which will be woven into the fabric of existing institutions. Urban intelligence functions also involve a major theoretical implication in that planning will be based on integrating and harnessing complexity science, urban complexity theories, sustainability science, urban sustainability theories, urban science, data science, and data-intensive science in order to fashion powerful new forms of simulation models and optimization methods. These can generate optimal designs and solutions that improve sustainability, efficiency, resilience, equity, and life quality. This is enabled by the kind of model-driven decision support systems associated with urban computing and intelligence.

With respect to strategic planning, big data analytics will allow to make evidence-based decisions in terms of policy and planning to improve sustainability. In other words, the analytical outcome of big data will be used as the evidence base for formulating the policies, plans, and strategies of sustainable cities and tracking their impact and effectiveness. Using a data-driven scientific approach to investigate all available evidence will lead to policy and planning decisions that are more effective in achieving the desired outcomes of sustainability as decisions are based on accurate and meaningful information. Urban computing and intelligence provides the systematic and rational approach required for evidence-based decision making in terms of analyzing available evidence to inform the policymaking and planning processes. This approach to decision making involves putting the best available evidence from research at the heart of policy design and planning and their implementation. The evidence-based approach to decision making strives to improve the efficiency and effectiveness of policymaking and planning processes by focusing on what works and what needs to be improved. Among the benefits of evidence-based approach to policymaking and planning are ensuring that policies and plans are responding to the real needs of citizens, highlighting the urgency of issues or problems which requires immediate attention, and enabling information sharing amongst different stakeholders in regard to best practices.

A fourth practical implication is associated with the comprehensive approach of the proposed model in regard to the transformations it entails and how these can be achieved to attain the future vision. This model will allow planners to design and develop the landscape of future cities while considering the different types of infrastructures, namely the built infrastructure, the smart infrastructure, the sustainable infrastructure, the social infrastructure, and the technological infrastructure. This in turn means implementing and integrating the strategies and pathways needed to bring about the needed transformations. For example, when designing the built infrastructure concerning the compaction strategies related to social sustainability, designers can simultaneously take into consideration the role of the technological infrastructure in improving the social infrastructure in terms of citizen participation, public safety, and healthcare services. This is to boost the benefits of social sustainability enabled by urban design (e.g., reducing crime and providing a feeling of safety through natural surveillance, improving social equity through better access to services and facilities, improved human health due to more cycling and walking, etc.).

The main methodological contribution of this study stems from reframing how to analyze, investigate, and develop a novel model for data-driven smart sustainable cities of the future. The research approach adopted led to the integration of a set of principles underlying several normative backcasting approaches with descriptive case study design to devise a framework for strategic data-driven smart sustainable city planning. This methodological framework will encourage and allow researchers to adopt a multiple, integrated approach to case study research as part of backcasting for building future models for urban sustainability, whether in relation to sustainable urbanism, smart urbanism, smart sustainable urbanism, or other future global paradigms of urbanites. In many of the previous futures studies conducted on urban sustainability with respect to the pathway-oriented and action-oriented approaches to backcasting, researchers tended to focus on single cases, and also needed to tailor the existing backcasting methodologies to their research objectives prior to conducting their futures studies. Moreover, the methodological framework adopted in the futures study can be applied to different urban domains and scales as well. It is also flexible when it comes to the number of cases that can be investigated for the purpose of integrating the resulting outcomes as a foundation for the different types of strategic planning processes of transformative change towards sustainability.

7.3. Future Work

This PhD study, being of an exploratory and interpretive nature, raises a number of opportunities for future research. More research will in fact be necessary to expand and further elaborate our novel findings. Here we make some suggestions for future work. As the PhD study is concerned with futures research, it is most relevant to direct attention at the subsequent steps of the strategic process of backcasting. In this respect, the final step (6) of backcasting analysis in the futures study should include the assessment of the developed future vision, with the goal this time to—create an actionable plan towards successful implementation and to put it into motion while addressing the responsibilities and roles of the key stakeholders concerned with the implementation of the results. This involves establishing a follow-up agenda containing activities for the different stakeholders involved in bringing about the transformations needed to attain the vision of the future, in addition to stakeholder support in regard to the shared vision and the commitment to the follow-up agenda. Following Step 6 of the futures study, Step 7 elaborates and defines action agenda and follow-up, and Step 8 embeds and initiates or stimulates follow-up activities. These may need to be combined due to the limited time and changes in stakeholder involvement. In other words, implementation and embedding can be changed into making a follow-up proposal, sketching a rough development and implementation trajectory, and analyzing what could or should be the contribution of different stakeholder groups. For example, the political actions and institutional responses (city government, regulatory body, industry, research community, etc.) that are required for the implementation of the vision and the policy measures implied in those actions and responses. Of importance also is the actions of other stakeholder groups, such as companies, cooperatives, public interest, advocacy groups, civil society, communities, and citizens.

Step 7 and Step 8 are best to be connected to real-word cities, which are to be chosen as cases of interest and relevance, with consideration of the opportunities, capabilities, and constraints of each city. In this regard, it would be useful to conduct a detailed stakeholder analysis as a way of studying a network in order to generate information on the relevant actors, understand their interests and agendas and influence on decision-making processes, and identify differing perspectives and avoiding conflicts. However, most of the time, when it comes to city development, contradictions, contentions, uncertainties, and even disputes emerge during the cooperation and interaction between government officials, policymakers, planners, developers, engineers, industry experts, thought leaders, and civil society as part of a comprehensive team. Nevertheless, this phenomenon is common in all city development projects and initiatives due to the difficulty of aligning and accommodating the interests and expectations of the different stakeholders of the city.

Moreover, governance is important when it comes to the actors involved in any transformative change. Adding governance and actors in the backcasting study makes it more socio-technically consistent and comprehensive, and can also identify if prevailing social structures restrain change. The purpose of this part of future research is to gain insights into how the concepts of stakeholder and governance together with politics and policy relate to the strategic planning process of transformative change towards sustainability with respect to its effectuation and implementation.

In addition to the two subsequent steps of backcasting, it would be interesting to carry out a wider and more varied examination and comparison of other cities from Scandinavian and European countries with respect to the models of urbanism underlying the whole strategic planning process of planning, with a view to revealing more general and recent trends in connection with the emerging model of data-driven smart sustainable cities. Taking up this in future research is indeed justified by the limitations associated with the futures study, which pertain to the number of the cases selected for investigation as well as the criteria for selection in regard to focusing on Swedish cities. Due to this bias in the case selection, it is conceivable to potentially discover more integrated design strategies and environmental technology solutions of sustainable cities and more advanced data-driven technology solutions of smart cities that support the synergistic and balancing integration of the three dimensions of sustainability.

Furthermore, there is a need for more in-depth qualitative analyses of the long-term social, cultural, political, and ethical implications of the adoption of big-data analytics and urban computing and intelligence in city development planning and operational management, despite their numerous advantages for improving and advancing sustainability. This implies that policy-makers and planners should be careful when employing these technologies when setting high expectations on their advancements.

Given the approach to the futures study adopted, we have not detailed exactly how we might demonstrate our research, but it should be highly applied, developed, and focused on real-world cities that are manifestly planning to be smart sustainable and those that are becoming smart sustainable in a less self-conscious manner as they tend to respond to emerging global trends and shifts by modernizing their ICT infrastructure based on the IoT and big data technologies. As part of future work, it will be worth selecting a series of urban places and urban spheres that are considered typical of these types, e.g., new planned smart sustainable cities, large cities that are clearly becoming smart sustainable such as those leading within the ecologically and technologically advanced nations in Europe, such as Denmark, Sweden, Germany, Norway, and the Netherlands. For example, cities that have particular problems, issues, and challenges pertaining to their contribution to and balancing of the goals of sustainability in the face of the escalating trend of urbanization, or those that stand on a spectrum of the smartness scale but need to embrace and make the best of the concept of sustainable development. Other cities whose compact or ecological form has been developed based on incremental and interactive processes involving many stakeholders over time and need to regenerate themselves in ways that combine the compact and ecological dimensions of sustainability prior to adopting data-driven technologies and solutions for sustainability. The underlying assumption is that the future of these cities might be assured by explicit development of a data-driven smart sustainable city ethos. In light of this, it is required to create a portfolio of tools for decision support on the basis of these demonstrators and to ensure that these are linked to key initiatives on data-driven smart sustainable cities to be developed by the major ICT companies of the world in collaboration with the city governments of existing sustainable cities or emerging smart sustainable cities

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Appendices

Appendix A: Selected Papers

Bibri Simon Elias and Krogstie John: "Smart Sustainable Cities of the Future: An Extensive Interdisciplinary Literature Review". Sustainable Cities and Society 2017; Volume (31) pp.183-212

P2: Bibri, Simon Elias: "On the Sustainability of Smart and Smarter Cities and Related Big Data Applications: An Interdisciplinary and Transdisciplinary Review and Synthesis". Journal of Big Data 2019; Volume 6.(25) pp. 1-64

P3: Bibri, Simon Elias and Krogstie, John: "A Scholarly Backcasting Approach to a Novel model for Smart Sustainable Cities of the Future: Strategic Problem Orientation ". Journal of Futures Studies 2019; Volume 6.(3) pp. 1-27

P4: Bibri, Simon Elias and Krogstie, John: "Generating a Vision for Smart Sustainable Cities of the Future: A Scholarly Backcasting Approach", European Journal of Futures Research; Volume 7.(5) s. 1-20.

P5: Bibri, Simon Elias: "A Methodological Framework for Futures Studies: Integrating Normative Backcasting Approaches and Descriptive Case Study Design for Strategic Data-Driven Smart Sustainable City Planning". Energy Informatics 2020; Volume 3.(31) pp. 1-42

P6: Bibri, Simon Elias, Krogstie, John and Kärrholm, Mattias: "Compact City Planning and Development: Emerging Practices and Strategies for Achieving the Goals of Sustainability". Developments in the built environment 2020; Volume 4 pp. 1-20

P7: Bibri, Simon Elias and Krogstie, John: "Smart Eco–City Strategies and Solutions: The Cases of Royal Seaport, Stockholm, and Western Harbor, Malmö, Sweden". Urban Science 2020; Volume 4.(1) pp. 1-42

P8: Bibri, Simon Elias and Krogstie, John: "The emerging Data–driven Smart City and its Innovative Applied Solutions for Sustainability: The cases of London and Barcelona". Journal of Energy Informatics 2020; Volume (3).5 pp. 1-42

P9: Bibri, Simon Elias and Krogstie, John: "Environmentally Data-driven Smart Sustainable Cities: Applied innovative Solutions for Energy Efficiency, Pollution Reduction, and Urban Metabolism". Energy Informatics 2020; Volume (3).29 pp. 1-59

P10: Bibri Simon Elias and Krogstie John: "Data-Driven Smart Sustainable Cities of the Future: A Novel Model of Urbanism and its Core Dimensions, Strategies, and Solutions". Journal of future Studies; Volume 25(2). pp. 77–94

P11: Bibri, Simon Elias and Krogstie John: "A Novel Model for Data-Driven Smart Sustainable Cities of the Future: A Strategic Roadmap to Transformational Change in the Era of Big Data" . Future Cities and Environment; Volume 7(1).3 pp. 1–25

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P12: Bibri, Simon Elias: "Data-driven Environmental Solutions for Smart Sustainable Cities: Strategies and Pathways for Energy Efficiency and Pollution Reduction". Euro-Mediterranean Journal of Environmental Integration 2020; Volume (5).66 pp. 1-6

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Smart Sustainable Cities of the Future: An Extensive Interdisciplinary Literature Review

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Engineering advance

Smart sustainable cities of the future: An extensive interdisciplinary literature review

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ABSTRACT

In recent years, the concept of smart sustainable cities has come to the fore. And it is rapidly gaining momentum and worldwide attention as a promising response to the challenge of urban sustainability. This pertains particularly to ecologically and technologically advanced nations. This paper provides a comprehensive overview of the field of smart (and) sustainable cities in terms of its underlying foundations and assumptions, state–of–the art research and development, research opportunities and horizons, emerging scientific and technological trends, and future planning practices. As to the design strategy, the paper reviews existing sustainable city models and smart city approaches. Their strengths and weaknesses are discussed with particular emphasis being placed on the extent to which the former contributes to the goals of sustainable development and whether the latter incorporates these goals. To identify the related challenges, those models and approaches are evaluated and compared against each other in line with the notion of sustainability. The gaps in the research within the field of smart sustainable cities are identified in accordance with and beyond the research being proposed. As a result, an integrated approach is proposed based on an applied theoretical perspective to align the existing problems and solutions identification for future practices in the area of smart sustainable urban planning and development. As to the findings, the paper shows that critical issues remain unsettled, less explored, largely ignored, and theoretically underdeveloped for applied purposes concerning existing models of sustainable urban form as to their contribution to sustainability, among other things. It also reveals that numerous research opportunities are available and can be realized in the realm of smart sustainable cities. Our perspective on the topic in this regard is to develop a theoretically and practically convincing model of smart sustainable city or a framework for strategic smart sustainable urban development. This model or framework aims to address the key limitations, uncertainties, paradoxes, and fallacies pertaining to existing models of sustainable urban form—with support of ICT of the new wave of computing and the underlying big data and context–aware computing technologies and their advanced applications. We conclude that the applied theoretical inquiry into smart sustainable cities of the future is deemed of high pertinence and importance—given that the research in the field is still in its early stages, and that the subject matter draws upon contemporary and influential theories with practical applications. The comprehensive overview of and critique on existing work on smart (and) sustainable cities provide a valuable and seminal reference for researchers and practitioners in related research communities and the necessary material to inform these communities of the latest developments in the area of smart sustainable urban planning and development. In addition, the proposed holistic approach is believed to be the first of its kind. That is, it has not been, to the best of one's knowledge, investigated or produced elsewhere.

Contents

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1. Introduction

It has been estimated by the United Nations that by 2050 66% of the world's population will live in cities (United Nations, 2015). This implies significant challenges pertaining to environmental and social sustainability (OECD, 2012). In addition, the form of contemporary cities has been viewed as a source of environmental and social problems. Cities consume about 70% of the world's resources and hence are major consumers of energy resources and significant contributors to greenhouse gas (GHG) emissions due to the density of urban population and the intensity of related economic and social activities, in addition to the inefficiency of the built environment. Therefore, contemporary debates in urban and academic circles continue to focus on the role of sustainability in urban planning and development in terms of responding to the substantial challenges arising from the rapidly evolving urbanization as well as the unsustainability of existing urban forms. The way forward for cities to better cope with the changing and restructuring conditions is to adopt the long–term approaches that focus on sustainability (see Bulkeley & Betsill, 2005). This is to mitigate the adverse effects that these cities might encounter as a result of stretching beyond the capacities and designs of urban systems accompanying urban growth (e.g. Antrop, 2004). In contemporary cities, urban systems—processes which operate and organize urban life in the form of built form, infrastructure, ecosystem services, human services, and administration—are under increasing pressure due to the enormous challenge of sustainability, coupled with the greatest wave of urbanization in history. The existing built environment is already associated with numerous environmental, social, and economic impacts, including unsustainable energy use and concomitant GHG emissions, increased air and water pollution, environmental degradation, land use haphazard, inappropriate urban design and related social deprivation and community disruption, ineffective mobility and accessibility, increased transport needs and traffic congestion, public safety and health decrease, but to name a few. Adding to this are the outdated (non–automated, non–digital) infrastructures within cities, which pose technical and physical problems (e.g. Colldahl, Frey, & Kelemen, 2013). In particular, the form of contemporary cities affects people, natural resources, habitat, and climate (e.g. Jabareen, 2006). These effects are set to worsen with increased urbanization due to the issues it engenders in relation to sustainability. Urban growth raises a variety of problems that tend to jeopardize the environmental, economic, and social sustainability of cities (e.g. Neirotti, De Marco, Cagliano, Mangano, & Scorrano, 2014). In more detail, the rapid urbanization of the world, albeit an emblem of social evolution, gives rise to numerous challenges associated with intensive energy consumption, endemic congestion, saturated transport networks, air and water pollution, toxic waste disposal, resource depletion, social inequality and vulnerability, public health decrease, and so on. In a nutshell, as a dynamic clustering of people, buildings, infrastructures, and resources (Bibri 2013), urbanization puts an enormous strain on urban systems, thereby stressing urban life in terms of the underlying operating and organizing processes, functions, and services.

The above intractable problems require evidently an unprecedented paradigm change to disentangle and overcome—i.e. newfangled ways of urban thinking grounded in a holistic approach and long–term perspective with respect to the conception, planning, and development of the built, infrastructural, operational, and functional forms of cities. Towards this end, there is an urgent need first to develop, apply, and mainstream innovative solutions and sophisticated methods in the area of urban planning and development. This urgency is also to overcome the challenges of urbanization (European Commission, 2014; United Nations, 2016). Therefore, ICT has recently become part of mainstream debate on urban sustainability as well as urbanization due to the ubiquity presence of urban computing and the massive use of urban ICT in urban systems and domains. Indeed, data sensing and information processing are being fast embedded into the very fabric of contemporary cities while wireless networks are proliferating on a hard–to–imagine scale (Batty et al., 2012; Bibri & Krogstie 2016b). This is underpinned by the recognition that the planning of cities as dynamic and evolving systems towards sustainability in terms of how they function and can be managed and developed necessitates smart, data–centric technologies. Against the backdrop of the unprecedented rate of urbanization, alternative ways of thinking about and conceiving of cities are materializing (see Batty, 2013a,b) as to how they can transition to the needed sustainable development in light of advanced ICT (see Bibri & Krogstie, 2016a,b). Besides, the way cities can intelligently be planned and developed has been of fundamental importance for strategic sustainable development to achieve the long–term goals of sustainability. To put it differently, ICT in its various forms (infrastructures, applications, data analytics capabilities, and services) is increasingly seen to provide unsurpassed ways to address a range of complex environmental challenges and rising socio–economic concerns facing contemporary cities. In fact, ICT is already enabling cities in many parts of the world to remain sustainable and thus livable in the face of staggering urbanization, growing social mobility, and ongoing transformation. An increasing urgency to find and adopt smart solutions is driven by urban growth in terms of seeking out ways to address the associated challenges and ensuing effects (see Nam & Pardo, 2011). Townsend (2013) portrays ICT development and urban growth as a form of symbiosis. This entails an interaction that is of advantage to or a mutually beneficial relationship between ICT and urban growth. By the same token, the planning of cities as complex systems towards sustainability requires innovative ideas and sophisticated methods and techniques (e.g. Colldahl et al., 2013; Kramers et al., 2013, 2014; Rotmans, van Asselt, & Vellinga, 2000; Shahrokni, Årman, Lazarevic, Nilsson, & Brandt, 2015). This entails the application of complexity sciences upon which ICT is founded (Bibri & Krogstie 2016a). Indeed, a large number of advanced technologies are being developed and applied in response to the urgent need for dealing with the complexity of the knowledge necessary for enhancing, harnessing, and integrating urban systems and facilitating collaboration and coordination among urban domains in the realm of smart sustainable urban planning and development (Bibri & Krogstie, 2016b). ICT plays a key role in smart sustainable urban planning (Bifulco, Tregua, Amitrano, & D'Auria, 2016). ICT development and sustainability awareness have resulted in an opportunity to rethink the way we plan cities (Höjer & Wangel, 2015) and to develop new ways of understanding and addressing urban challenges and problems (Batty et al., 2012).

When discussing sustainability and ICT and thus sustainable practices and smart solutions for cities, reference is made to the two concepts of sustainable cities and smart cities. Scholars from different disciplines and practitioners from different professional fields have, over the past two decades or so, sought a variety of sustainable city models as well as smart city approaches that can contribute to sustainability and its improvement. Compact city and eco–city (e.g. Jabareen, 2006; Jenks et al. 1996a,b; Joss 2010, 2011; Joss, Cowley, & Tomozeiu, 2013; Neuman, 2005; Register, 2002) are the most prevalent models of sustainable city (e.g. Hofstad, 2012; Jabareen, 2006; Kärrholm, 2011; Rapoport & Verney, 2011). However, the challenge continues to motivate and induce academics and planners as well as policymakers and decision–makers to work collaboratively to put forward new approaches into redesigning and rearranging urban areas across many spatial scales to achieve the required level of sustainability, especially in relation to integrating its environmental, economic, social, and cultural dimensions. The ultimate goal revolves around developing more convincing and robust sustainable city models. This has been one of the most significant intellectual challenges and research endeavors for more than two decades. This implies that it has been difficult to, in addition to translating sustainability into the built form of cities, evaluate whether and the extent to which the so–called sustainable urban forms contribute to the goals of sustainable development (see, e.g., Jabareen, 2006; Kärrholm, 2011). Indeed, existing models of sustainable urban form still pose several conundrums and raise numerous issues—when it comes to their development and implementation as to their contribution to the fundamental goals of sustainable development. This pertains to limitations, uncertainties, paradoxes, and fallacies. One implication of this is that more innovative solutions and more sophisticated approaches are needed to overcome these challenges and issues, and important and relevant questions in this regard involve how these forms should be monitored, understood, analyzed, and planned to improve sustainability. The underlying argument is that urban systems have been in themselves complex in terms of their operation, management, assessment, and planning in line with the vision of sustainability. Here comes the role of ICT into play given its foundation on the application of complexity sciences to urban systems and problems (Batty et al., 2012; Bibri & Krogstie, 2016b). With that in mind, while the development of compact city and eco–city has been, for about two decades, the preferred response to the challenge of sustainability (see, e.g., Hofstad, 2012; Jabareen, 2006; Jenks, Burton, & Williams, 1996a; Joss 2011; Kärrholm, 2011; Rapoport & Vernay, 2011; Roseland, 1997), the development of smart city with its various faces has come to the fore in recent years as a promising response to the same challenge (e.g. Al Nuaimi, Al Neyadi, & Nader, 2015; Batty et al., 2012; Neirotti et al., 2014)—by developing smart solutions for sustainability, optimizing efficiency in urban systems, and enhancing the quality of life of citizens. This can occur through connecting urban systems and assessing their sustainability performance; eliminating redundancy in urban operations and services; and pinpointing which urban domains, facilities, and networks to couple, coordinate, and integrate. The smart solutions have proven track records as to enhancing many processes and practices in large cities. Indeed, it is in such cities that the key to a better world—which is held by ICT—will be most evidently demonstrated (Batty et al., 2012). The prosperity of many cities and their ability to address their complex challenges through advanced ICT is one of the key reasons why much attention has been given to smart city as an urban development strategy. Cities can evolve in ways that intelligently address the environmental concerns and meet the social needs of their citizens (Murray, Minevich, & Abdoullaey, 2011), as they are the incubators, generators, and transmitters of innovative ideas and smart solutions for solving many challenges. However, like sustainable city models, existing smart city approaches present significant challenges and raise many issues—when it comes to their development and implementation as to their incorporation of the fundamental goals of sustainable development. This pertains to deficiencies, inadequacies, and misunderstandings. Regardless, of most relevance to highlight is that there is a lack of connection between smart cities and sustainable cities, despite the great potential and proven role of ICT in supporting cities in their transition towards sustainability, especially in relation to the operation, management, and planning of urban systems (e.g. Batty et al., 2012; Bibri & Krogstie 2016a,b; Kramers, Höjer, Lövehagen, & Wangel, 2014). It is important to understand how the concepts of smart cities and sustainable cities relate to each other (Bifulco et al., 2016).

In light of the above, recent research endeavors have started to focus on how to incorporate sustainability in smart city approaches and to smarten up sustainable city models (e.g. Al Nuaimi et al., 2015; Batty et al., 2012; Bibri & Krogstie, 2017; Kramers et al., 2014; Neirotti et al., 2014; Shahrokni et al., 2015). One optimal way of doing so is by integrating the two perspectives as urban development strategies in an attempt to achieve the required level of sustainability with respect to urban operations, functions, services, and designs. This holistic approach has been seen to hold great potential to address the challenge of, or provide solutions for moving towards, urban sustainability (e.g. Batagan 2011; Höjer & Wangel, 2015; Kramers et al., 2014; Murray et al., 2011). Thereby, the concept of smart sustainable cities has come to the fore, and is rapidly gaining momentum as a holistic approach to urban development and as an academic pursuit, not least in ecologically and technologically advanced societies (Bibri & Krogstie, 2016a). That is to say, it is increasingly becoming an important concept not only in urban research and planning, but also in city policy and politics, thus generating worldwide attention as a powerful framework for strategic sustainable urban development (see, e.g., Al-Nasrawi, Adams, & El-Zaart, 2015; Höjer & Wangel, 2015; ITU, 2014). It is worth noting that the emergence of this new techno–urban phenomenon has been particularly fueled by what is labeled 'ICT of the new wave of computing'—i.e. a combination of various forms of pervasive computing, the most prevalent of which are Ubiquitous Computing (UbiComp), Ambient Intelligence (AmI), the Internet of Things (IoT), and Sentient Computing (SenComp) (Bibri & Krogstie, 2016a). Besides, we live in a world where computing and ICT have become deeply embedded into the very fabric of contemporary cities, i.e. urban operations, functions, services, and designs are pervaded with computation and intelligence. In view of that, for existing sustainable city models, in particular, to prosper, they need to embrace what ICT has to offer as innovative solutions and sophisticated methods for sustainability in order to smarten up as to making urban living more sustainable over the long run—in an increasingly computerized urban society. This is predicated on the assumption that advanced ICT offers tremendous potential for monitoring, understanding, probing, assessing, and planning cities, which can be leveraged in the improvement of urban sustainability.

The purpose of this paper is to provide a comprehensive overview of the field of smart (and) sustainable cities in terms of its underlying foundations and assumptions, state–of–the art research and development, opportunities and horizons, emerging scientific and technological trends, and future planning practices. This extensive literature review endeavors to present a detailed analysis, critical evaluation, and interdisciplinary synthesis of the available qualitative research covering the topic of smart and sustainable cities in line with the concepts that we have set ourselves for the research, with a particular emphasis on cross–disciplinary issues. The questions this literature review addresses are the following:

What are the key scholarly sources that are relevant, authoritative, and topical?

What are the key theories, concepts, and academic discourses?

What are the intellectual origins and definitions of the topic?

What are the main questions and problems that have been addressed to date?

What are the major issues, debates, and challenges relating to the topic?

What are the available and worth exploring research opportunities and horizons in the field?

What are the emerging scientific and technological trends and future planning practices in the field?

The approaches to these questions are primarily intended to enhance our understanding and knowledge of the flourishing field of smart sustainable cities. The motivation for this paper—and hence the rationale behind our pursuit of research within the area of smart sustainable urban development—is threefold: (1) the interdisciplinary academic field of smart sustainable cities is evolving into a scholarly and realist techno–urban enterprise; (2) it is gaining momentum as a societal pursuit in ecologically and technologically advanced nations; and (3) it has become of high importance and relevance to capture further and invigorate the application demand for the smart solutions for urban sustainability and its advancement that emerging and future urban ICT can offer. The main added value of this paper lies in highlighting the need for ICT development and innovation to be linked with sustainable development, and thus related future investment to be justified by environmental concerns and socio–economic needs, rather than technical advancement and industrial competitiveness. Other added values involve its thoroughness (i.e. including numerous sources), topicality (i.e. addressing subjects of immediate relevance and importance due to their relation to current urban phenomena), and original contribution (i.e. new terminology for understanding and discussing the field and novel deep insights about the field as a result of analyzing and synthesizing the various available works).

The remainder of this paper proceeds as follows. Section 2 outlines the search, selection, and organization approaches into the literature review, as well as its purposes in the context of our study. In Section 3, we introduce, describe, and discuss the main conceptual, theoretical, and discursive constructs that make up our study. In Section 4, we present a survey of related research work and critically discuss, analyze, and evaluate key issues, debates, and challenges. Section 5 highlights and encapsulates research opportunities and horizons for smart sustainable cities. In Section 6, we shed light on future urban planning practices and emerging scientific and technological trends. We present our concluding remarks, contributions, and final thoughts in Section 7.

2. Literature review search, selection, and organization approaches and purposes

The field of smart sustainable cities is profoundly interdisciplinary. Hence, this literature review involves the exploration of an extensive and broad array of material (including journal articles, books, reports, conference proceedings, dissertations, theses, and policy documents) at the intersection of various disciplinary areas of relevance to the intended research topic, and focuses on the existing and established theory and qualitative research. It is carried out based on an integration of technical and social perspectives (Levy & Ellis, 2006; Webster & Watson, 2002). Accordingly, we defined a review protocol and developed a review method as a means to indicate the questions to be addressed, search strategies to retrieve articles and other documents from various sources, inclusion and exclusion criteria for identifying relevant articles and other documents, and abstract review protocols.

2.1. Search strategy and scholarly sources

To find out what has already been written on the topic of smart sustainable cities, an extensive search of the literature was performed. The objective of our search strategy was to identify the relevant studies into smart (and) sustainable cities. Of importance to underscore here is that the preliminary selection of available material was done in line with the research being proposed or the problem being investigated, using a variety of academic sources that are relevant, current, and authoritative. That is, the search for the intended published work was directed with our main research question (thesis) in mind: How to advance the contribution of existing sustainable urban forms to the goals of sustainable development with support of emerging and future ICT—enabled by the new wave of computing—under what is labelled 'smart sustainable cities' of the future? This entails an effective integration of the typologies and design concepts of the prevalent models of sustainable city with the ICT solutions pertaining to the most advanced models of smart city, with the aim of improving urban sustainability. However, we used standard search strategies involving querying a variety of relevant academic or scholarly sources, namely electronic (cross–disciplinary) databases as well as Google scholars. We searched independently a number of international journals and conference proceedings. The main contributions came from quality journal articles based on Scott, 1990 four criteria for assessing quality: authenticity, credibility, representation, and meaning. The examined period as to sustainable cities was (mainly) from 2005 to 2016, and as to smart cities was from 2005 to 2016. Regarding smart sustainable cities. it was only around the mid 2010 s when the concept emerged, so the examined period was from 2015 and onward. The searched keywords included 'smart cities'; 'smart cities AND future'; 'smart cities AND sustainability'; 'sustainable cities'; 'sustainable urban forms'; 'compact city'; eco–city'; 'ambient city'; 'sentient city'; 'ubiquitous city'; 'the IoT AND smart city'; 'smart sustainable cities'; 'big data analytics AND smart cities'; 'big data analytics AND sustainability'; 'context–aware computing and smart cities'; 'context–aware computing AND sustainability'; as well as derivatives of these terms. We used these keywords to search against such categories as the articles' keywords; title; and abstract to produce some initial insights into the field on focus. To note; due to the shortcomings associated with relying on the keyword approach (levy & Ellis, 2006); we additionally used backward literature search (backward authors; backward references; and previously used keywords) and forward literature search (forward authors and forward references) (Webster & Watson, 2002). For concepts; theories; and academic discourses; the searched keywords included 'sustainability'; 'sustainable development'; 'sustainability science'; 'urban sustainability'; 'sustainable urban development'; 'urban planning; "urban design"; 'urban ICT'; 'urban computing'; 'smart cities'; 'sustainable cities'; and 'smart sustainable cities'.

2.2. Inclusion and exclusion criteria

The key questions for which previous and current research or results from qualitative analyses on smart (and) sustainable cities were sought were employed to further select the relevant documents, in particular journal articles, for reading. This selection was initially bounded with the aforementioned research question. This is underpinned by the recognition that once we have our research question we will be able to refine and narrow down the scope of our reading, although there may seem to be hundreds of sources of information that appear pertinent. With that in mind, to be considered an article that provided information or evidence on the questions being addressed, the article had to cover one of the conceptual subjects or thematic categories intended to be elaborated on and discussed or analyzed and evaluated. Our focus was on articles that provided definitive primary information from a systematic review. While certain methodological guidelines were deemed essential to ensure the validity of the review, it was of equal importance to allow flexibility in the application of the proposed approach to capture the essence of research within the rather flourishing interdisciplinary field of smart sustainable cities. The whole idea was to ensure that we 'accumulate a relatively complete census of relevant literature' (Webster & Watson, 2002). With the above in mind, to ensure an effective outcome, we excluded articles that did not meet specific criteria in terms of relevance to the research questions being addressed. We therefore assessed each of the published articles accordingly. Specifically, we scored them for the inclusion of issues and themes relating to these questions, keeping in mind the aim of relating the literature to and explaining our main research question. As to abstract review, each citation and the abstract were reviewed to assess relevance to the interdisciplinary review and to ensure reliable application of the inclusion and exclusion criteria. And inclusionary discrepancies were resolved by re–review. The process enabled us to refine and narrow down the scope of our reading. The exclusion involved specific criteria in terms of the quality of the research on the topic, including information source adequately searched and applicable, inclusion/exclusion criteria comprehensible and applicable, and the approaches into combining results applicable. However, we attempted at the outset of the literature process to read quite broadly on the topic to enrich our understanding of the field. Indeed, this is useful for establishing the perspective that our research will take in terms of how it will extend or enhance the existing knowledge in the field, as well as for refining our topic in terms of working out where there are gaps in the existing knowledge, which has provided us with a niche for our study. In a nutshell, the literature review needs to explain and relate to the main research question. In addition, we discovered during the search that some advanced aspects of emerging and future ICT in the realm of smarter cities in relation to sustainability were part of (ongoing) studies not yet reported in the literature.

2.3. A combination of organizational approaches

This literature review is organized using a combination of structural approaches, namely thematic, inverted pyramid, and the benchmark studies. This means that the research is divided into sections representing both the conceptual subjects as well as the thematic categories for the topic on focus. The discussion of the related literature is organized accordingly while, when appropriate, starting from a broad perspective and then dealing with more and more specific perspectives from studies associated with the research problem. In doing so, the discussion focuses on the major writings considered as significant in the field of smart (and) sustainable cities.

2.4. Specific purposes

The literature review is typically performed to serve many purposes. This tends to differ slightly depending on the academic nature and level of the study being carried out. Here the literature review was done for our study to serve specific purposes, which include the following:

- To determine what has been done in terms of the research being proposed.
- To provide an overview of key concepts, theories, and discourses
- To study the definitions adopted in the research, with the purpose of espousing them for our study.
- To broaden our horizons and gain insight into the problem at hand.
- To evaluate and synthesize the existing information in line with the concepts set for our study.
- To discuss and analyze the relevant information written about the topic.
- To provide a solid background and theoretical foundation for our study.
- To familiarize ourselves with the latest developments in the field.
- To highlight the strengths, weaknesses, omissions, and conflicting evidence of the existing knowledge, thereby providing a critique of the research.
- To discover major relationships between different research results by comparing various studies.
- To identify the gaps in the existing research that our study is endeavoring to address, positioning our work in the context of previous research and creating a research space for it.
- To situate our work within prominent research trends to establish its significance.
- To produce a rationale and establish the need for our study and thus justify its originality.

3. Conceptual, theoretical, and discursive foundations and assumptions

3.1. Sustainability and sustainable development

The notion of sustainability was born from the realization that the predominant paradigm of social, economic, and urban development was oblivious to the risks of and triggering environmental crises as well as to the implications of and worsening social decays, causing ecological and social deprivation and imperiling future life. Sustainability epitomizes a holistic, long–term perspective based on the premise of consciously and incessantly going with the grain of nature and providing the conditions for deploying the frameworks necessary for its operationalization and its translation into practices in a more intelligent way in order to reach a sustainable society. Generating immediate worldwide attention upon the widespread dissemination of the concept of sustainable development in the late 1980s, followed by an unprecedented prevalence and wide adoption of related strategies, sustainability embodies a unique productive and constitutive force as a large–scale societal discourse. As a societal thinking paradigm, sustainability is espoused to guide and configure societal development in its prominent spheres, including science and innovation, technology, economy, urban planning, policy, politics, and institutionalization. The underlying premise is that it is grounded in an all–embracing understanding of the challenges and problems facing society, which is necessary for making all–inclusive decisions and taking well–informed actions for its long–term benefit.

There is no canonical or definite definition of sustainability. It is a difficult concept to delineate given its contested, philosophical, normative, and multifaceted nature, in addition to the complexity of the socio–ecological system to which it is applied (e.g. Bibri, 2015b; Huckle, 1996; McManus, 1996; Molnar, Morgan, & Bell, 2001). In general terms, sustainability can be conceived of as a state in which society doesn't undermine the natural and social systems, i.e. where the natural system is not subject to resource depletion and intensive consumption, hazardous substances, and concomitant environmental risks, and, as of equal importance, where the social system doesn't render people subject to conditions that inhibit their ability to satisfy their needs and aspirations. Undermining natural and social systems can occur through pollution, environmental degradation/ecological deprivation, health decrease, social instability, social injustice, and social hazard.

Sustainable development is a process of change and strategic approach to achieve the long–term goals of sustainability: a balanced socio–ecological system (Bibri 2013, 2015b). It has emerged as a global response to the environmental crises triggered by anthropogenic activities and the escalating social inequalities and injustices. The concept of sustainable development was introduced by the Bruntland Report in 1987, in which it denotes 'development that meets the needs [and aspirations] of the present without compromising the ability of future generations to meet their own needs.' (WCED, 1987) However, this classic definition has been misconstrued and misused and generated several critiques. As a result, the concept has become widely multifarious, highly contested, and oftentimes contradictory and oxymoronic (e.g. Hopwoodil et al., 2005; Jacobs, 1999; Jöst, 2002; Munda, 1997; Murcott, 1997; Redclift, 1987, 2005). The lack or absence of a more universal definition of sustainable development has given rise to multiple interpretations and philosophical underpinnings, which has consequently triggered or led to an explosion of environmental, social, and economic indicators. However, as one among many other alternative definitions in the literature, sustainable development is described by Bibri, 2015b as 'the planned and strategic development processes of working towards a balance of economic, environmental, and social values and goals, i.e. a balance of the need for economic development and prosperity with environmental protection and integrity and social equity and justice. The premise is to conciliate the continuity of these—conflicting, competing, and sometimes contradictory—forces' or realms.

3.2. Sustainability science

Just like the definition of sustainability, consensual definition of sustainability science is difficult to pin down. Broadly, sustainability science entails advancing knowledge on how the natural and human systems interact in terms of the underlying (changing) dynamics, with the purpose of designing, developing, implementing, evaluating, and perennially enhancing engineered systems as practical solutions and interventions that support the idea of the socio–ecological system in balance, as well as nurturing and sustaining linkages between scientific research and technological innovation and policy and public administration processes in relevance to sustainability. The concept is defined as 'the cultivation, integration, and application of knowledge about Earth systems gained especially from the holistic and historical sciences. . .coordinated with knowledge about human interrelationships gained from the social sciences and humanities, in order to evaluate, mitigate, and minimize the consequences. . .of human impacts on planetary systems and on societies across the globe and into the future.' (Kieffer et al., 2003) As a flourishing academic discipline, sustainability science has emerged in the early 2000 s (e.g. Clark & Dickson, 2003; Clark, 2007; Kates, Clark, Corell, Hall, & Jaeger, 2001). As an interdisciplinary field, it brings together disciplines across the natural sciences, social sciences, and applied and engineering sciences. As a research field, it probes the complex mechanisms and patterns involved in the profound interactions between social, environmental, and engineered systems to understand their behavioral patterns and changing dynamics and to contribute to developing (rather upstream) solutions for tackling complex challenges associated with systematic degradation of these systems and with concomitant perils to human well–being. That is, challenges that imperil the integrity of the planet's life support systems and compromise the future of human life. This research field seeks to give the 'broad–based and crossover approach' of sustainability a solid scientific foundation. It also provides a critical and analytical framework for sustainability (Komiyama & Takeuchi, 2006), and 'must encompass different magnitudes of scales (of time, space, and function), multiple balances (dynamics), multiple actors (interests), and multiple failures (systemic faults)' (Reitan, 2005). To add, sustainability science can be thought of or viewed as 'neither "basic" nor "applied" research but as a field defined by the problems it addresses rather than by the disciplines it employs; it serves the need for advancing both knowledge and action by creating a dynamic bridge between the two' (Clark, 2007).

From a broader perspective of sustainability science, some views highlight the need to probe the root causes of the fundamental unsustainability of the predominant paradigms of technological, economic, and societal development. In this line of thinking, Bibri, 2015b analyzes the implications of ICT of the new wave of computing as technological developments for environmental and societal sustainability. Brown (2012) contends that sustainability science must involve the role of technology in as well aggravating the unsustainability of social practices as in tackling the problems these practices generate, and also the study of the societal structures as to material consumption. The attempt to grasp the integrated whole of the socio–ecological system in terms of the complex social and multidimensional environmental aspects and problems necessitates globally integrated political consensus and collaboration between institutional, social, economic, scientific, and technological disciplines, as well as the active engagement of citizens, communities, organizations, and institutions. One key mission of sustainability science is to aid in coordinating cross–disciplinary integration necessary as a critical step towards a global joint effort and concerted action. In addition, the way in which sustainability science as a scholarly community can best contribute to the understanding and implementation of the goals of sustainable development should be based on an in–depth critical analysis and evaluation through scenario analysis, scientific research, technological innovation, stakeholder relationships, participatory decision–making, and policy recommendations and impacts. In a nutshell, to achieve these goals requires taking an all–inclusive approach by mobilizing diverse actors, factors, and resources.

3.3. Urban sustainability and sustainable urban development

The concepts of sustainability and sustainable development have been applied to urban planning and design since the early 1990s (e.g. Wheeler & Timothy, 2010), thereby the emergence of the notions of urban sustainability and sustainable urban development. Urban sustainability denotes a desired state in which the urban society strives for achieving a balance between environmental protection and integration, economic development and regeneration, and social equity and justice within cities as long–term goals through the strategic process of sustainable urban development as a desired trajectory. Thereby, it seeks to create healthy, livable, and prosperous human environments with minimal demand on resources (energy, material, etc.) and minimal impact on the environment (toxic waste, air and water pollution, hazardous chemicals, etc.), to draw on Bibri (2013). This overall goal entails fostering linkages between scientific and social research, technological innovation, institutionalized and organizational practices, and policy design and planning in relevance to urban sustainability. Urban sustainability tends to be cast in terms of four dimensions: the form, the environment, the economy, and equity, which should all—given their interdependence, synergy, and equal importance—be enhanced over the long run in a sustainable urban society. Accordingly, contemporary cities should retain a balance between physical, environmental, economic, and social concerns and goals. To achieve this long–term goal requires an urban development strategy that facilitates and contributes to the design, development, implementation, evaluation, and improvement of urban systems and other practical interventions within various urban domains that promote urban sustainability in terms of replenishing resources, lowering energy use, lessening pollution and waste levels, as well as improving social justice, stability, and safety. This is what sustainable urban development is about. This concept signifies, in other words, the development (and/or redevelopment) of cities in ways that provide livable and healthy human environments with enhanced quality of life and well–being in conjunction with decreased demand on resources and lessened environmental impacts, to iterate, thereby steering clear of leaving a burden on the future generations due to potential environmental degradation or ecological deprivation. Richardson, 1989 defines sustainable urban development as 'a process of change in the built environment which foster economic development while conserving resources and promoting the health of the individual, the community, and the ecosystem.' In a nutshell, sustainable urban development is characterized as achieving a balance between the development of and equity in the urban areas and the protection of the urban environment. However, conflicts among the goals of sustainable urban development to achieve the long–term goals of urban sustainability are challenging to deal with and daunting to overcome. This has indeed been, and continues to be, one of the toughest challenges facing urban planners and scholars as to decision–making and planning in the realm of sustainable cities (Bibri & Krogstie, 2017), not to mention smart cities due to the multidimensional risks they pose to environmental sustainability (Bibri & Krogstie, 2016a). Despite sustainable urban development seeking to provide an enticing, holistic approach into evading the conflicts among its goals, these conflicts 'cannot be shaken off so easily', as they 'go to the historic core of planning and are a leitmotif in the contemporary battles in our cities', rather than being 'merely conceptual, among the abstract notions of ecological, economic, and political logic' (Campbell, 1996). Even though these goals co–exist uneasily in contemporary cities, sustainable urban development as a long–range objective for achieving the aim of urban sustainability is worthy for urban planners, as they need a strategic process to achieve the status of sustainable cities, to increase the contribution of smart cities to sustainability, and to spur the development of smart sustainable cites. As expressed by Campbell, 1996, planners will in the upcoming years 'confront deep–seated conflicts among economic, social, and environmental interests that cannot be wished away through admittedly appealing images of a community in harmony with nature. Nevertheless, one can diffuse the conflict, and find ways to avert its more destructive fall–out.' To put it differently, sustainable urban development advocates can—and ought to—seek ways to make the most of all three value–sets at once. This is in contrast to keeping on playing them off against one another. With that in mind, the synergistic and substantive effects of sustainable development on forms of urban management, planning, and development require cooperative effort, collaborative work, and concerted action from diverse urban stakeholders in order to take a holistic view of the complex challenges and pressing issues facing contemporary cities.

In the context of this paper, the focus is on the smart dimension of urban sustainability and sustainable urban development. In this regard, smart urban sustainability consists of four dimensions: physical, environmental, economic, and social, which should be enhanced in terms of goals and be in balance in terms of concerns over the long run—with support of urban computing and ICT—to achieve the sought after smart form of urban sustainability. This can occur through the process of change and strategic approach of sustainable urban development that—in seeking to foster and promote sustainable urban forms, environmental integration, economic development, and social equity as interrelated goals—relies on smart ICT in terms of innovative solutions and novel approaches by unlocking the untapped potential for sustainable transformation that ICT embodies in its morphing and disruptive power as an enabling, integrative, and constitutive technology. The respective change process and strategic approach ought to be driven by linking the research agenda of urban computing innovation and urban ICT development with the agenda of sustainable urban development, thereby justifying ICT investment and its orientation by environmental concerns and socio–economic needs in this context. This endeavor should be supported by pertinent institutional structures and practices.

3.4. Urban planning and design

Several notable books (e.g. Jacobs, 1961; Lynch, 1981; Mumford, 1961; McHarg, 1995; Wheeler & Timothy, 2010) have been written on the subject of urban planning (and development). They have approached it from a variety of perspectives, including social, cultural, political, economic, physical, spatial, and ecological. Urban planning is the process of guiding and directing the use and development of land, urban environment, urban infrastructure, and related ecosystem and human services—in ways that ensure the maximum level of economic development, high quality of life, wise management of natural resources, and efficient operation of infrastructures. In more detail, urban planning entails drawing up, evaluating, and forecasting an organized, coordinated, and standardized physical arrangement of a city and the underlying infrastructural systems, processes, functions, and services, i.e. the built form (buildings, streets, neighborhoods, residential and commercial areas, parks, etc.), urban infrastructure (transportation, water supply, communication systems, distributed networks, etc.), ecosystem services (energy, raw material, water, air, food, etc.), human services (public services, social services, cultural facilities, etc.), and administration (delivery of services and provision of facilities to citizens, implementation of mechanisms for adherence to established regulatory frameworks, policy recommendations, various technical and assessment studies, etc.). The ultimate aim of urban planning is to make cities more sustainable and hence livable and attractive places. As an academic discipline, urban planning is concerned with research and analysis, sustainable development, strategic thinking, environmental planning, transportation planning, land–use planning, landscape architecture, civil engineering, policy recommendations, implementation, administration, and urban design (e.g. Nigel, 2007).

Urban design overlaps with urban planning in terms of perspectives and practices. Urban design as an interdisciplinary field involves urban planning, landscape architecture, and civil engineering (Van Assche, Beunen, Duineveld, & de Jong, 2013), in addition to such sub–strands as sustainable urbanism, sustainable urban design, and strategic urban design. Dealing with the design and management of the public domain and the way this domain is experienced and used by urbanites, urban design denotes the process of designing, shaping, and reorganizing cities with respect to physical structures, arrangements, and typologies. The focus in sustainable urban design is on the larger scale of buildings, streets, neighborhoods, districts, parks, public infrastructure, and public spaces, with the primary aim of making urban living more environmentally sustainable and urban areas more attractive and functional (e.g. Aseem 2013; Boeing, Church, Hubbard, Mickens, & Rudis, 2014; Larice & MacDonald, 2007; McHarg, 1995). In this regard, urban design entails making connections between forms for human settlements and environmental sustainability, economic viability and social equity, the built environment and ecosystems, people and the natural environment, and movement and urban form. These issues are also of interest to the field of urban planning. In the context of this paper, the emphasis is on the smart planning of sustainable urban forms as a set of integrated typologies and design concepts (namely density, compactness, diversity, mixed–land use, sustainable transport, and ecological design) as organized, coordinated, and standardized physical arrangements and spatial organizations. The way cities are designed, developed, and planned is of importance for sustainable development and thus sustainability (e.g. Egger, 2006). McHarg (1995) describes and illustrates an ecologically sound approach to urban planning and design, and Wheeler and Timothy (2010) provide a range of perspectives on sustainable urban planning and development.

3.5. Urban ICT and urban computing

Information and communication technology (ICT) theory has been applied to almost all human endeavors and thus spheres of society. In the sphere of urban planning and development, the concept of ICT refers to a set of urban infrastructures, architectures, applications, systems, and data analytics capabilities—i.e. constellations of hardware and software instruments across several scales connected through wireless, mobile, and ad hoc networks which provide continuous data regarding the physical, spatiotemporal, infrastructural, operational, functional, and socio–economic forms of the city. These technological components are employed for sensing, collecting, storing, coordinating, integrating, processing, analyzing, synthesizing, manipulating, modeling, simulating, managing, exchanging, and sharing urban data for the purpose of monitoring, understanding, probing, and planning modern cities to achieve particular goals. To put it differently, the aim of applying ICT to urban domains and systems and thus using the underlying core enabling technologies and data–centric applications is to better comprehend how cities function and can be managed as complex systems to derive new theories, devise new solutions, formalize and implement new methods, and study and evaluate processes. This entails a variety of ways of remedying a wide range of problems affecting the long–term health and efficiency of the city as well as the quality of life of its citizens.

At the technical level, urban ICT includes hardware and software components. The former encompass sensors (e.g. RFID, GPS, infrared sensors, smart sensors, wearable devices, etc.), computers and terminals, smartphones, Internet infrastructure, wireless communication networks, telecommunication systems, database systems, cloud computing infrastructure, and middleware architecture. The latter includes all kind of software applications operating and running on these hardware systems, including big data analytics techniques (e.g. data mining, machine learning, statistical analysis, and natural language processing), database integration and management methods, modeling and simulation methods, visualization methods, real–time operation methods, enterprise integration methods, decision support systems, and communication and networking protocols. ICT spans over scores of urban domains and subdomains and hence can be integrated in built form, infrastructure, architecture, networks, facilities, services, spatial organizations, and physical objects, as well as attached to citizens and spread along the trajectories they follow during their daily activities. Urban ICT can be best spoken of based on the context of use, e.g., smart transport, smart mobility, smart traffic, smart energy, smart planning, smart governance, smart environment, smart healthcare, smart education, smart safety, and smart parks (e.g. Bibri & Krogstie 2016a,b).

Urban computing has been used interchangeably with urban ICT; however, there is still a distinction between the two concepts. Drawing on Bibri, 2015b, urban ICT theory deals with the application of ICT in and its effects on urban society, and urban computing theory is concerned with the way ICT systems are created and operate in relation to urban planning and design. Entailing a process of big and heterogeneous data collection, integration, analysis, and synthesis (Zheng, Capra, Wolfson, & Yang, 2014), urban computing has emerged as a set of computational tools, techniques, and processes to tackle the pressing issues engendered by the rapid urbanization and the challenge of sustainability facing cities by using various kinds of urban data, e.g., human mobility data, spatiotemporal data, traffic flow data, environmental data, energy data, transport data, and socio–economic data. It is an interdisciplinary field where computing as a range of scientific and technological areas (e.g. computer and information science, information technology and systems, computer and software engineering, and wireless and sensor networks) and city–related or urban planning fields (e.g. environmental planning, transportation planning, land use planning, landscape architecture, civil engineering, urban design, ecology, economy, and sociology) converge in the context of urban spaces. Accordingly, urban computing deals with the study, design, development, and implementation of computing technology in urban areas and systems. Specifically, it is concerned with designing and constructing urban–oriented systems and applications and making them behave intelligently as to decision support to serve multiple urban goals; representing, modeling, processing, and managing various kinds of urban data; collecting information and discovering knowledge for various purposes, and so forth. Urban computing employs many of the technological paradigms introduced by the new wave of computing (the integration and large–scale use of various forms of pervasive computing, including UbiComp, AmI, the IoT, and SenComp), i.e. an era when, in the urban context, computer technology in all its forms disappears into urban environments and recedes into the background of urban life, to draw on Weiser (1991). The new wave of computing share the same core enabling technologies, namely sensing devices, computing infrastructures, data processing platforms, and wireless communication networks. These are to function unobtrusively and invisibly in the background of urban life to help improve urban operational functioning, enhance the quality of life, facilitate urban daily activities, understand the nature of urban phenomena, and plan or foresee the future of cities. The new wave of computing is associated with the amalgamation of the most prevalent visions of ICT. For a detailed account of the dominant visions of ICT in terms of their definitions, characteristics, differences, and overlaps, the reader is directed to Bibri and Krogstie (2016a).

3.6. Smart cities

There are different views regarding the origin of the concept 'smart city' in the literature. According to Gabrys (2014), the roots of the concept date back to the 1960s under what is called the 'cybernetically planned cities', and in urban development plans, it has figured in proposals for networked cities since the 1980s. Dameri and Cocchia (2013) claim that the concept was introduced in 1994. Neirotti et al. (2014) state that the origin of the concept can be traced back to the smart growth movement in the late 1990s. Batty et al. (2012) confirm that it is only until recently that the concept has been adopted in city planning through the movement of smart growth. Speaking of which, it entails increasing urban efficiency with regard to energy, transportation, land use, communication, economic development, service delivery, and so forth. Indeed, a smart city represents essentially efficiency, which is based on intelligent management of urban systems using ICT. Further, it is the period after the emergence of smart city projects supported by the European Union since 2010 that has witnessed a proliferation of writings and academic publications on the topic of smart city (Jucevicius, Patašienė, & Patašius, 2014).

Nowadays, smart city is a catchphrase that draws increased attention among research institutes, universities, governments, policymakers, and ICT companies. Notwithstanding the wide use of the concept today, there is still unclear and inconsistent understanding of its meaning (e.g. Ahvenniemi, Huovila, Pinto-Seppä, & Airaksinen, 2017; Al Nuaimi et al., 2015; Angelidou, 2015; Batty et al., 2012; Caragliu et al., 2009; Chourabi et al., 2012; Khan, Anjum, Soomro, & Tahir, 2015; Marsal-Llacuna, Colomer-Llinàs, & Meléndez-Frigola, 2015; Neirotti et al., 2014; Wall & Stravlopoulos, 2016). In view of that, a great number of definitions have been suggested different emphases, although academics, ICT experts, and policymakers converge on the use of ICT across all domains of smart cities, and hence on considering it as an inseparable facet thereof. A wide variety of smart city definitions are available (Albino, Berardi, & Dangelico, 2015). In addition, smart city has many faces that tend to vary on the basis of such aspects as the way ICT is applied, the digital means by which it is coordinated and integrated, the extensiveness of its use, and the degree of its pervasiveness. These faces include virtual cities, cyber cities, digital cities, networked cities, intelligent cities, knowledge cities, and real–time cities, amongst many other nomenclatures, as well as hybrid cities which combine two or more of these names. Adding to these cities are the ones that are inspired by ICT of various forms of pervasive computing, such as ubiquitous cities, ambient cities, sentient cities, and cities as Internet–of–everything (e.g. Böhlen & Frei, 2009; Crang & Graham, 2007; Kyriazis, Varvarigou, Rossi, White, & Cooper, 2014; Lee, Han, Leem, & Yigitcanlar, 2008; Shepard, 2011; Shin, 2009; Thrift, 2014). These cities are the object of the next subsection. However, common to all smart cities as urban development strategies or approaches is the idea that ICT is, and will be for many years to come, central to urban operations, functions, services, and designs.

There is no canonical or universally agreed upon definition of smart city. It is a difficult concept to pin down or strictly delineate, and can still be considered a vague notion. It is often context–dependent—i.e. diverse smart city projects, initiatives, and endeavors are based on particular target objectives, available resources, financial capabilities, regulatory and policy frameworks, political structures, and so on. It also depends on the state–of–the–art research and development in the field of ICT as to the available solutions with respect to architectures, technologies, applications, systems, models, methods, computational analytics, and so forth. As an example of target objectives, Batty et al. (2012) identify a number of projects pertaining to smart cities of the future, including mobility and travel behavior; modeling urban land use; integrated databases across urban domains; sensing, networking, and the impact of social media; participatory governance and planning structures; modeling network performance; transport and economic interactions; and decision support as urban intelligence. As regards to the financial capabilities, the growing interest in the concept of smart city, driven by the needs to address and solve urbanization challenges, has led to several investments in ICT development and deployment manifested in the high number of jointly–funded research endeavors as well as smart city initiatives and implementation projects (Ahvenniemi et al., 2017). In all, it is evident that smart city lacks a shared definition, and thus it is hard to identify common trends.

In essence, there are two mainstream approaches to smart city: (1) the technology and ICT–oriented approach and 2) the people–oriented approach. Specifically, there are smart city strategies which focus on the efficiency and advancement of hard infrastructure and technology (transport, energy, communication, waste, water, etc.) through ICT, and strategies which focus on the soft infrastructure and people, i.e. social and human capital in terms of knowledge, participation, equity, safety, and so forth (Angelidou, 2014). As an example of the first approach, Kitchin (2014) conceives of smart city as one that monitors and integrates all of its critical infrastructures, optimizes its resources, plans its activities, and maximizes services. In this line of thinking, Marsal-Llacuna et al. (2015) state that by using ICT and data analytics technologies, smart cities aim to monitor and optimize existing infrastructure, to increase collaboration among economic actors, to provide more efficient services to citizens, and to support innovative business models across private and public sectors. As to the second approach, Neirotti et al. (2014) describe smart city as a way of enhancing the life quality of citizens. Smart city entails human and social factors, apart from physical and technological factors (Aguilera, Galan, Campos, & Rodríguez, 2013). Lombardi et al. (2011) emphasize additional soft factors such as participation, safety, and cultural heritage. Other views tend to put emphasis on services (e.g. Belanche, Casaló, & Orús, 2016; Lee, Hancock, & Hu, 2014). Belanche et al., 2016 underscore the increased use of urban services to attain efficiency and sustainability. Angelidou (2014) underscores the role of ICT to achieve prosperity, effectiveness, and competitiveness.

It is important to highlight the body of the literature focusing on the role of human and social capital, in addition to new technologies, in developing smart cities that aim to improve economic, social, and environmental sustainability (e.g., Batty et al., 2012; Giffinger, Kramar, Kalasek, Pichler-Milanovic, & Meijers, 2007; Hollands, 2008; Nam & Pardo, 2011; Neirotti et al., 2014). This stream of literature is concerned with smart cities as urban innovations based on ICT that aims at harnessing physical and social infrastructures as well as natural and knowledge resources for economic regeneration, environmental efficiency, and public and social service enhancement. One of the most cited definitions in this regard is the one advanced by Caragliu, Del Bo, and Nijkamp (2009), which states that a city is smart 'when investments in human and social capital and traditional (transport) and modern (ICT) communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory governance.' This definition is based on a model that has been used as a classification system—developed through six distinct dimensions, namely smart mobility, smart environment, smart living, smart people, smart economy, and smart governance—against which smart cities can be gauged or evaluated in terms of their development in the direction of smartness. This model is said to represent a holistic understanding by what it entails in terms of the complementary nature of these dimensions. Though it doesn't provide a prioritization of these dimensions as to their contribution to sustainability, nor does it specify how they can add to urban development and planning practice in terms of sustainability. Nevertheless, this connotation of smart city is seen as a strategic devise to highlight the growing role and potential of ICT in enabling and catalyzing sustainable urban development processes. Indeed, it goes beyond technological investments and advancements to include environmental, social, and economic developments with sustainability in mind. In extending this definition, Pérez-Martínez et al. (2013, cited in Ahvenniemi et al., 2017) describe smart cities as 'cities strongly founded on ICT that invest in human and social capital to improve the quality of life of their citizens by fostering economic growth, participatory governance, wise management of resources, sustainability, and efficient mobility, whilst they guarantee the privacy and security of the citizens.' In a similar vein, Batty et al. (2012, p. 481 482) conceive of smart cities as cities 'in which ICT is merged with traditional infrastructures, coordinated and integrated using new digital technologies', and where 'intelligence functions. . .are able to integrate and synthesize. . .[urban] data to some purpose, ways of improving the efficiency, equity, sustainability, and quality of life in cities.' In all, smart cities endeavor to amalgamate advanced digital technologies and urban planning approaches to find innovative and smart solutions that contribute to improving livability and enhancing sustainability (see Toppeta 2010). Smart initiatives can be used to promote environmental sustainability (Kramers et al., 2014). This implies that sustainability is not an integral part of all the definitions of smart city. This is taken up as a research issue in the next section.

3.7. Smarter cities

The increasing convergence, prevalence, and advance of urban ICT is giving rise to new faces of cities that are quite different from what has been experienced hitherto on many scales. These cities are labelled 'smarter cities' because of the magnitude of ICT and the profusion of data as to their embeddedness and use in urban systems and domains. The prospect of smart cities getting smarter is becoming the new reality with the massive proliferation of sensing, computing, data processing, communication, and networking technologies across various spatial scales. Smarter cities include ubiquitous cities (e.g. Batty et al., 2012; Lee et al., 2008; Shin, 2009), ambient cities (e.g. Böhlen & Frei, 2009; Crang & Graham, 2007), sentient cities (e.g. Shepard, 2011; Thrift 2014); and cities as an Internet of everything (e.g. Kyriazis et al., 2014). They are seen as future visions of smart cities. The initiatives of smarter cities enabled by ICT of various forms of pervasive computing (namely UbiComp, AmI, SenComp, and the IoT) in several countries across Europe, the USA, and Asia are increasingly considered as national urban development projects that center on strengthening the role of ICT, especially big data analytics and context–aware computing, in urban operations, functions, services, and designs as to management, planning, and development to advance urban sustainability (Bibri and Krogstie, 2016a).

In light of the above, the concept of smarter cities is built upon the core characteristic features of the prevalent ICT visions in terms of the ubiquity of computing in urban systems, massive use of ICT in urban domains, and its numerous benefits and opportunities for cities and citizens. That is, the pervasion of sensors technologies, information processing systems, and computational analytics and communication capabilities into urban environments and thereby the omnipresence and always–on interconnection of computing resources and services across many spatial and temporal scales, to draw on Bibri, 2015a. Accordingly, the conceptualization of smarter cities is associated with the ever–growing and deep embeddedness of advanced ICT into the very fabric of the city in terms of operations, functions, designs, and services. It indeed differentiates smarter cities as emerging and future cities from the aforementioned conceptualizations of common smart cities. In this respect, Townsend, 2013 defines a smart city as an urban environment where ICT 'is combined with infrastructure, architecture, everyday objects, and even our own bodies to address social, economic and environmental problems.' Piro, Cianci, Grieco, Boggia, and Camarda (2014) describe it 'as an urban environment which, supported by pervasive ICT systems, is able to offer advanced and innovative services to citizens in order to improve the overall quality of their life.' According to Su, Li, and Fu (2011), a smart city mainly focuses on embedding the next–generation of ICT into every conceivable object or all walks of life, including roads, railways, bridges, tunnels, water systems, buildings, appliances, hospitals, and power grids, in every corner of the world, and constituting the IoT. Chourabi et al. (2012) define a smart city as a city which strives to become smarter in the sense of making itself more efficient, livable, equitable, and sustainable. Here the word 'smarter' implies the use of advanced ICT in order to improve efficiency, sustainability, equity, and the quality of life. This is in line with what constitutes smart cities of the future according to Batty et al. (2012). The basic idea is that future smart cities have greater potential than existing smart cities for advancing their contribution to the goals of sustainable development. This is due to the current capabilities as well as the prospective advancements pertaining to big data analytics and context–aware computing as advanced forms of ICT, in addition to their increasing amalgamation in various urban domains and systems in terms of the underlying core enabling technologies, namely sensor devices, computing infrastructures, data processing platforms, and wireless communication networks (e.g. Al Nuaimi et al., 2015; Batty et al., 2012; Bibri & Krogstie, 2016b; Böhlen & Frei, 2009; DeRen, JianJun, & Yuan, 2015; Kamberov, 2015; Khan, Kiani, & Soomro, 2014a, Khan, Pervez, & Ghafoor, 2014b; Khan, Anjum, Soomro, & Tahir, 2015; Shepard, 2011; Solanas et al., 2014). In all, a smarter city can be described as a city where advanced ICT is combined with physical, infrastructural, architectural, operational, functional, and ecological systems across many spatial scales, as well as with urban planning approaches, with the aim of improving efficiency, sustainability, equity, and livability. Smarter cities entail that diverse context–aware and big data applications operating across cloud computing infrastructures can monitor what is happening in urban environments (in terms of situations, events, activities, processes, behaviors, locations, spatiotemporal settings, environmental states, socio–economic patterns, and so on) and process, analyze, interpret, visualize, and react to the outcome through decision support systems and strategies at varying ways—be it in relation to smart energy, smart grid, smart street and traffic lights, smart transport, smart mobility, smart healthcare, smart education, smart safety, smart planning, smart governance, or smart buildings—across many spatial scales (Bibri & Krogstie, 2016b). Here, smartness should primarily be focused on the goals of sustainable development rather than on only technology and the efficiency of smart solutions. There has been a shift in cities striving for smartness targets instead of sustainability goals (Marsal-Llacuna et al. 2015).

3.8. Sustainable cities: sustainable urban forms

There are various definitions of what a sustainable city should be. Based on the literature on compact city, eco-city, and new urbanism as the most prevalent and sustainable models of sustainable urban form as instances of sustainable city (e.g. Bohl, 2000; Hofstad, 2012; Jabareen, 2006; Jenks et al., 1996a,b; Joss, 2010; Girardet, 2008; Rapoport and Vernay, 2011; Williams, 2009) a sustainable city can be understood as a set of approaches into practically applying the knowledge of urban sustainability and environmental technologies to the planning and design of existing and new cities or districts. In the context of this paper, a sustainable city can be described as an urban environment designed with the primary aim of contributing to improved environmental quality and protection and social equity and well–being over the long run, which can be attained through adopting sustainable development strategies to foster advancement and innovation in built environment, infrastructure, operational functioning, planning, and ecosystem and human service provisioning, while continuously optimizing efficiency gains. This entails working strategically towards mitigating the environmental impacts derived from the intensive consumption of energy, while promoting social justice, safety, and stability. In more detail, sustainable cities strive to maximize efficiency of energy and material resources, create a zero–waste system, support renewable energy production and consumption, promote carbon–neutrality and reduce pollution, decrease transport needs and encourage walking and cycling, provide efficient and sustainable transport, preserve ecosystems, emphasize design scalability and spatial proximity, and promote livability and sustainable community.

Sustainable development has significantly impacted the development of city models in terms of different dimensions of sustainability (e.g. Girardet, 2008; Hofstad, 2012; Jabareen, 2006; Joss, 2011; Williams et al., 2000). Unquestionably, it has inspired and motivated a generation of urban scholars and practitioners into a quest for the immense opportunities enabled and created by the development of sustainable urban forms—i.e. the contribution that these forms can make as to lowering energy use and lessening pollution and waste levels, while improving human life quality and well–being. Therefore, the idea of applying the concept of sustainable development to urban form has intensively been investigated and discussed by researchers and planners during the last decade (see Kärrholm, 2011). According to Lynch, 1981, urban form is 'the spatial pattern of the large, inert, permanent physical objects in a city.' In more detail, urban form as aggregations of repetitive elements denotes amalgamated characteristics pertaining to land use patterns, spatial organizations and other urban design features, as well as transportation systems and environmental and urban management systems (Handy, 1996; Williams et al., 2000). A sustainable urban form can be conceived of as an urban form for human settlements that seeks to meet the required level of sustainability by enabling the urban systems (built form, infrastructure, ecosystem services, human services, and administration) and thus the urban domains to function in a constructive way (Bibri & Krogstie, 2017). Using a thematic analysis approach, Jabareen (2006) classifies sustainable urban forms into four models entailing overlaps in their concepts, ideas, and visions: (1) compact city, (2) eco-city, (3) neotraditional development (new urbanism), and (4) urban containment. Compact city emphasizes density, compactness, and mixed-land use; eco-city focuses on ecological and cultural diversity, passive solar design, renewable resources, urban greening, environmental management, and environmentally sound policies; and neotraditional development emphasizes sustainable transport, mixed-land use, diversity, compactness, greening, and design coding. This paper is concerned with the first three urban forms in terms of integrating the underlying (relevant) typologies and design concepts as well as environmental and urban management systems with the core enabling technologies and their novel applications pertaining to ICT of the new wave of computing (particularly in relation to big data analytics and context-aware computing). The rationale for focusing on these three urban forms lies in the fact that they have been ranked as the most sustainable, with the compact city being the first, the eco-city the second, and the neotraditional development the third, according to Jabareen (2006). From a general perceptive, a typology refers to the grouping of 'artifacts describing different aspects of the same or shared characteristics' (Bibri 2015a). For a detailed account and discussion of the typologies as well as design concepts of sustainable urban forms, the reader is directed to Jabareen (2006) or Bibri and Krogstie (2017).

3.9. Smart sustainable cities

The smart sustainable city is a new techno–urban phenomenon. Hence, the term only became widespread during the mid–2010s (e.g. Al-Nasrawi et al., 2015; Bibri and Krogstie 2016a,b; Höjer & Wangel, 2015; Kramers, Wangel, & Höjer, 2016; Rivera, Eriksson, & Wangel, 2015) as a result of several intertwined global shifts. The interlinked development of sustainability awareness, urban growth, and technological development have recently converged under what is labelled 'smart sustainable cities' (Höjer & Wangel, 2015). The concept has emerged on the basis of five different developments, namely sustainable cities, smart cities, urban ICT, sustainable urban development, sustainability and environmental issues, and urbanization and urban growth (Höjer & Wangel, 2015). The term 'smart sustainable city', although not always explicitly discussed, is used to denote a city that is supported by a pervasive presence and massive use of advanced ICT, which, in connection with various urban domains and systems and how these intricately interrelate, enables cities to become more sustainable and to provide citizens with a better quality of life. In more detail, it can be described as a social fabric made of a complex set of networks of relations between various synergistic clusters of urban entities that, in taking a holistic and systemic approach converge on a common approach into using and applying smart technologies that enable to create, disseminate, and to mainstream solutions and methods that help provide a fertile environment conducive to improving the contribution to the goals of sustainable development. Here, ICT can be directed towards and effectively used for collecting, analyzing, and synthesizing data on every urban domain and system involving forms, structures, infrastructures, networks, facilities, services, and citizens. And these data can be utilized to develop urban intelligence functions as well as build urban simulation models to gain deep and predictive insights for strategic decision–making associated with sustainability. The combination of smart cities and sustainable cities, of which many definitions are available, has been less explored as well as conceptually difficult to delineate due to the multiplicity and diversity of the existing definitions. ITU (2014) provides a comprehensive definition based on analyzing around 120 definitions, 'a smart sustainable city is an innovative city that uses···ICTs and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social and environmental aspects.' Another definition put forth by Höjer and Wangel (2015, p. 10), which is deductively crafted and based on the concept of sustainable development, states that 'a smart sustainable city is a city that meets the needs of its present inhabitants without compromising the ability for other people or future generations to meet their needs, and thus, does not exceed local or planetary environmental limitations, and where this is supported by ICT.' This entails unlocking and exploiting the potential of ICT as a critical driver for environmental, social, and economic development, where ICT is conceptualized as an enabling and constitutive technology, thereby its transformational effects as to addressing the challenge of urban sustainability.

4. Related research work and key issues, debates, and challenges

In the emerging field of smart sustainable cities, research is inherently interdisciplinary and remarkably heterogeneous, and thus involves a plethora of issues, debates, and challenges that need to be addressed. This is essential for identifying new research opportunities and hence embarking on research endeavors on the basis of what has been investigated as questions and problems to date. The ultimate aim is to develop novel integrated frameworks or convincing comprehensive models that can play a role in spurring the development of smart sustainable cities, which aim at achieving their full potential in terms of the required level of sustainability and the integration of its dimensions. Successful frameworks are models are to have a high replicative capacity favorable to mainstreaming the needed transition to smart sustainable urban planning and development.

4.1. Smart (and smarter) cities

It is useful to point out that most of the issues, debates, and challenges discussed here in relation to smart cities apply, by extension, to smarter cities.

4.1.1. Research strands

The topic of smart cities brings together a large number of previous studies, including research directed at conceptual, analytical, and overarching levels, as well as research on specific technologies and their potentials and opportunities. Indeed, recent years have witnessed a great interest in and a proliferation of academic publications on the topic of smart cities. This reflects the magnitude and diversity of research within the field. The existing body of research is rapidly burgeoning, where the emphases and aims tend to be varied, as manifested in researchers' miscellaneous contributions to the conceptualization, design, development, and implementation of smart cities. From a general perspective, the field of smart cities merges broad streams of scholarship, which entail various strands of research. One strand of research is concerned with the theory and practice of urban computing, applied urban science, and urban ICT. This line of work addresses questions pertaining to urban sensing, urban informatics, big data analytics, context–aware computing, cloud computing infrastructures, data processing platforms, urban simulation models and intelligence functions, database integration, wireless technologies and networks, decision support systems, and so on. These varied technologies are applied to diverse urban domains (e.g. transport, mobility, energy, environment, water, waste, planning, design, education, healthcare, safety, governance, and economy) to achieve efficiency and better management (e.g. Angelidou, 2014; Batty, 2013a,b; Batty et al., 2012; Belanche et al., 2016; ChuanTao et al., 2015; DeRen et al., 2015; Gonzales & Rossi, 2011; Harrison & Donnely, 2011; Hung-Nien, Chiu-Yao, Chung-Chih, & Yuan-Yu, 2011; Jucevicius et al., 2014; Khan et al., 2015; Kitchin 2014; Lombardi et al., 2011; Marsal-Llacuna et al., 2015; Paroutis, Bennett, & Heracleous, 2013; Piro et al., 2014; Townsend, 2013; Zheng et al., 2014). This strand of research focuses mainly on technological advancement, use, and application for efficiency and management purposes, which tend to prevail in the field of smart cities. Our study is rather concerned with the role of ICT in advancing urban sustainability, in particular in relation to smarter cities as future faces of smart cities and their integration with existing sustainable cities.

Remaining on the same strand of research, a large body of conceptual work on smart cities has attempted to develop definitions and models to provide both a joint understanding of the concept of smart city, as well as a basis for further discussions on what this urban development approach aspires to deliver as to different aspects of smartness, though with less emphasis on sustainability. Adding to this academic endeavor is a large body of analytical work which has endeavored to investigate numerous propositions—in the light of emerging and future ICT—about what makes a new city badge or an existing city regenerate itself as smart, why a city uses ICT to develop new urban intelligence functions, and how a city develops urban services using modern ICT, among other things. Accordingly, early research work has tended to conceptualize, describe, classify, or rank the phenomenon of smart city based on the use of modern ICT in relation to a wide variety of urban operations, functions, designs, and services. Whereas recent research has typically focused on analyzing different projects, prospects, and initiatives and their possible urban impacts, with an emphasis on specific technologies and their applications, such as big data analytics, urban informatics, context–aware computing, and cloud computing, along with the challenges involved in achieving various smart city statuses. It is worth noting that, as this literature shows, there is a great deal of diversity among smart cities, and in this sense, it is pertinent to view the smart city as an ambition which can be for varied objectives and shaped by diverse disruptive technologies, and which there will be multiple ways to achieve. Of importance to underscore in this regard is that the so–called advanced ICT is sometimes used without any contribution to sustainability.

Another strand of research looks at the impacts ICT has on how we think about and conceive of cities in the sense of propelling us to rethink or alter some of the core concepts through which we analyze, operate, organize, assess, plan, and value urban life towards creating more sustainable ways of dwelling in and interacting with urban environments (e.g. Al Nuaimi et al., 2015; Batty et al., 2012; Böhlen & Frei, 2009; Shepard, 2011; Solanas et al., 2014). A key line of work within this strand tends to focus on integration proposals from a more conceptual perspective. The underlying idea is that some smart city approaches can be combined with some sustainable city models (e.g. Al-Nasrawi et al., 2015; Höjer & Wangel, 2015; Kramers et al., 2014), or the other way around. In the latter case, the aim evolves around enhancing the contribution of sustainable cities to sustainability with support of smart ICT. This is anchored in the underlying assumption that ICT is founded on the application of the complexity and data sciences which help to address the complex challenges and problems of sustainability. This tends, though, to involve mostly the infrastructural, operational, and functional aspects of sustainable cities, rather than the physical and spatial facets in terms of integrating them with technologies for better understanding, analysis, assessment, and planning purposes. Indeed, any kind of integration involving smart ICT and sustainable development requires a holistic approach into enabling cities to realize their potential as to their contribution to sustainability. In this regard, cities that stand on a spectrum of the sustainability scale can embrace and exploit smart development initiatives. By the same token, cities that stand on a spectrum of the smartness scale can embrace and exploit sustainable development initiatives. In this line of thinking, recent research endeavors (e.g. Ahvenniemi et al., 2017; Al Nuaimi et al., 2015; Batty et al., 2012) have started to focus on how to enhance smart city approaches in an attempt to achieve the required level of sustainability with respect to urban operations, functions, services, and designs. The best cities are those that support the generation of creative ideas and, more importantly, promote sustained development (Jacobs, 1961). Besides, for existing smart cities to thrive, they need to leverage their informational landscape in ways that enable them to incorporate and sustain their contribution to sustainability. In all, the main premise underlying the recently suggested integration proposals is to highlight that smart cities hold great potential to advance urban sustainability—if ICT advancement, use, and application can be directed for this goal. As smartness targets and sustainability goals are interconnected and thus smart cities tend to share similar goals as sustainable cities (Ahvenniemi et al., 2017), it is important to understand the link between the concepts of smart city and sustainable city (Bifulco et al., 2016), to iterate.

Another strand of research, which relates to the above one, focuses on the deficiencies or inadequacies associated with the sustainability of smart cities. The main issue being addressed and discussed is that not all the definitions of smart city incorporate the goals of sustainable development. According to Höjer and Wangel (2015), the existing concepts of smart city set up no baseline for sustainability, nor do they define what sustainable development is, although defining this concept is crucial to know the purposes for which smart ICT should be used, as well as to assess whether (or the extent to which) smart ICT contributes to the goals of sustainable development or delivers the desired outcomes in this regard. As echoed by Kramers et al. (2014), the concept of smart city says little about how any substance behind the smart solutions links to sustainability, and particularly has little to do with environmental concerns or solutions. In line with this thinking, in studying the concept of smart city through a lens of strategic sustainability, Colldahl et al. (2013) argue that while the concept of smart city is a powerful approach into enabling cities to become sustainable due to its potential to address some sustainability challenges by improving efficiency in urban systems, in addition to having an innovative and forward–thinking approach to urban planning, it is currently associated with shortcomings with regard to sustainability, i.e. it 'does not necessarily allow for cities to develop in a sustainable manner'. And there are various approaches that can be espoused to mitigate these shortcomings so that smart cities can evolve towards sustainability in a more effective way. One of which is to endeavor to explicitly incorporate the goals of sustainable development in the concept of smart city and to work towards developing smart cities in ways that direct ICT development and innovation towards primarily increasing their contribution to these goals. Especially, topical studies have highlighted the need for smart cities to pursue this path, and have also called for caution when encountering current smart city initiatives. In a very recent study, Ahvenniemi et al. (2017) used 16 existing smart city and sustainable city assessment frameworks (8 related to sustainable city and 8 related to smart city) to examine how smart cities compare with sustainable cities as to both commonalities and differences. They compare these frameworks as performance measurement systems with respect to 12 application domains (namely natural environment; built environment; water and waste management; transport; energy; economy; education, culture, science and innovation; well–being; health and safety; governance and citizen engagement; and ICT) and 3 impact categories (environmental, economic, and social sustainability) involving 958 indicators altogether. The authors observe a much stronger focus on modern ICT and what it entails in terms of smartness in the smart city frameworks as to social and economic indicators, but a lack of environmental indicators. They conclude that smart cities need to improve their sustainability with support of advanced ICT, and suggest on the basis of the gap between smart city and sustainable city frameworks further development of smart city frameworks and redefinition of the concept of smart city. Accordingly, they suggest that the assessment of smart city performance should use impact indicators that measure the contribution of smart cities to sustainability and thus to the environmental, economic, and social goals of sustainable development. Kramers et al. (2014) suggest that the concept of smart sustainable city can be used when as a way of emphasizing initiatives where smartness is directed towards promoting environmental sustainability. As supported by Höjer and Wangel (2015), smart cities become sustainable when ICT is employed for improving sustainability.

Much of the aforementioned technical literature on smart cities focuses on specific technologies and their potentials and opportunities. Specifically, the state of research in the realm of smart cities—a burgeoning scholarly interdisciplinary field and science–based, techno–urban enterprise—shows varied focuses of topical studies as to the potential of new technologies and their novel applications and services. This entails bringing advanced solutions for diverse complex problems related to such urban domains as transport, mobility, environment, energy, science and innovation, governance, and economy, as well as providing a plethora of new online and mobile services to citizens to improve the quality of their life with respect to education, healthcare, safety, well–being, accessibility, participation, and so forth. However, while ICT progress in this regard is rapid and manifold, it seems to happen ad hoc in the context of smart cities when new technologies and their applications become available, rather than grounded in a theoretically and practically focused overall approach—e.g. the most needed and urgent solutions that ICT can offer in the context of sustainability as an overarching urban application domain. In addition, to develop smart solutions of less relevance to environmental concerns and socio–economic needs is not the most effective way of driving ICT development and innovation in the context of smart cities. What is alternatively, needed, or rather what smart solutions ought to be created for, is a realistic tackle of the most pressing problems (e.g. energy inefficiency, environmental inefficiency, urban isolation, social injustice, and inaccessibility to opportunities). As to energy efficiency, for instance, Kramers et al. (2014) argue that the available opportunities need to be explored thoroughly and investigated as to how they can best support the implementation of ICT solutions to turn the potentials into real energy savings, and concurrently ICT industry needs to learn how best to design and implement the so–called smart solutions that lower energy usage. However, at this stage, there is much focus on technical dimensions as to ICT development and innovation, which pertains to all existing smart city approaches. Moreover, smart cities are associated with shortcomings in terms of lacking a holistic orientation as to integrating environmental, economic, and social considerations and goals of sustainability with technological opportunities. Hence, it is high time to link technological progress with the agenda of sustainable development and thus to justify future ICT investments by environmental concerns and socio–economic needs in the context of smart cities.

4.1.2. Scientific challenges and environmental and social risks

There are numerous and diverse challenges facing existing and future smart cities. Here the focus is on the most relevant ones in the context of our study. With reference to smart cities of the future, Batty et al. (2012p. 481–482) identify and elucidate several scientific challenges, namely 'to relate the infrastructure of smart cities to their operational functioning and planning through management, control and optimization; to explore the notion of the city as a laboratory for innovation; to provide portfolios of urban simulation which inform future designs; to develop technologies that ensure equity, fairness, and realize a better quality of city life; to develop technologies that ensure informed participation and create shared knowledge for democratic city governance; and to ensure greater and more effective mobility and access to opportunities for urban populations.'

Furthermore smart cities pose many risks to environmental sustainability (e.g. Bibri & Krogstie, 2016a; Greenfield, 2013; Hollands, 2008) due to the ubiquity of computing and the massive use of ICT across urban domains and systems. Driving this line of research are questions involving the way smart cities should measure and identify risks, uncertainties, and hazards (e.g. Batty et al., 2012) associated with ICT and set safety standards. This pertains not only to environmental sustainability, but also to social sustainability with regard to equity, fairness, participation, privacy, security, digital divide, and so on (e.g. Colldahl et al., 2013; Hollands, 2008; Murray et al., 2011). But the most eminent threat of ICT in the context of smart cities lies in its multidimensional effects on the environment (e.g. Bibri & Krogstie, 2016a). The real challenge lies in estimating the potential for curbing energy usage in a meaningful way in the sense of mitigating concomitant environmental impacts. The underlying assumption is that ICT as an enabling and constitutive technology is embedded into a much wider socio–technical landscape (economy, institutions, policy, politics, and social values) in which a range of factors and actors other than techno–scientific ones are involved (Bibri & Krogstie, 2016a). Therefore 'without careful implementation in combination with other measures, ICT solutions might also result in increased energy use instead of a reduction, either directly or in other parts of the energy system. . . [I]n order to establish the full impact of implemented ICT solutions, it is important to take into account all direct and indirect changes resulting from this, including the impact from the ICT solution's entire lifecycle. This also points to the importance of combining its implementation with policy and planning instruments, so as to ensure that the efficiency gains actually lead to a reduced use of energy.' (Kramers et al., 2014).

4.1.3. Smart city frameworks and infrastructures

While the literature shows a diversity of smart city frameworks, the one developed by Giffinger et al. (2007): the European Smart Cities Ranking, remains the most widely quoted, used, and applied in the field. It has been developed to enable the comparison of cities and to assess their development towards the needed direction. Accordingly, it has been used as a classification system—based on six distinct dimensions, namely smart mobility, smart environment, smart living, smart people, smart economy, and smart governance—against which smart cities can be gauged. Each dimension comes with a set of factors or criteria that evaluate success under that dimension. In this regard, a city identifies, based on the examination of its current state of smart development, the areas that might necessitate further improvements and then attempt to meet the necessary conditions so as to be able to regenerate itself as smart. In doing so, it can set goals based on its unique circumstances by pursuing the six dimensions in terms of related visions or prospects (Giffinger et al., 2007; Steinert, Revital, Phillippe, Veiga, & Witterns, 2011). Other smart city frameworks (e.g. Chourabi et al., 2012; Correia & Wuenstel, 2011; Neirotti et al., 2014) tend to differ slightly from the aforementioned one by combining, rearranging, extending, or renaming the defining characteristics or constituting features (i.e. relevant application domains) of smart cities. There are also other smart city performance assessment systems, such as Albino et al. (2015), Lazaroiu and Roscia (2012), and Lombardi et al. (2012).

Another set of frameworks has been developed for certain urban domains. In this regard, some frameworks have been proposed to benchmark cities and to assess the smartness of their transportation systems (e.g. Debnath, Chin, Haque, & Yuen, 2014; Garau, Masala, & Pinna, 2016), urban mobility (e.g. Garau, Masala, & Pinna, 2015), environment (e.g. Neirotti et al., 2014), or quality of life (e.g. Khan et al., 2015). In relation to sustainability, Ahvenniemi et al., 2017 state, quoting, Marsal-Llacuna et al. (2015), 'the smart city assessment builds on the previous experiences of measuring environmentally friendly and livable cities, embracing the concepts of sustainability and quality of life but with the important and significant addition of technological and informational components'. A study conducted by Bifulco et al. (2016) addresses the connections between the technologies enabling the smart city characteristics as conceptualized in the framework proposed by Giffinger et al. (2007) and the goals of sustainability. While the authors outline a new research avenue for the development of frameworks that amalgamate ICT with sustainability in, and new indicators for the evaluation of, smart interventions, no details are provided as to how to develop such frameworks in terms of the technological and urban components needed to achieve the purpose.

In addition, a wide variety of smart city infrastructures (e.g. Al-Hader and Rodzi 2009; DeRen et al., 2015; Khan, Ludlow, McClatchey, & Anjum, 2012, Khan et al., 2015; Khan & Kiani, 2012; Khan et al., 2014a,b; Kiani & Soomro, 2014; Nathalie, Symeon, Antonio, & Kishor, 2012) have been proposed and some of them have been applied in recent years. These infrastructures are based on cloud computing and tend to focus on technological aspects (especially big data analytics, context–aware computing, development and monitoring, etc.), urban management, privacy and security management, or citizen services in terms of the quality of life. There have been no research endeavors undertaken to develop comprehensive or integrated smart city infrastructures for addressing the challenge of sustainability. But there have been some attempts to address some aspects of environmental sustainability. For example, Lu et al. (2011) propose a framework for multi–scale climate data analytics based on cloud computing. Speaking of the climate in this context, there is still a risk of a mismatch between urban climate targets and the opportunities offered by ICT solutions (Kramers et al., 2014).

4.2. Sustainable cities

4.2.1. Research strands

There is a large body of work available on sustainable cities. The field is remarkably heterogeneous, entailing a diversity of research questions and problems that have been addressed to date in the context of urban sustainability. Thus, the topic of sustainable cities brings together a large number of previous studies, including research directed at conceptual, analytical, philosophical, and overarching levels, as well as specific research on urban forms and their typologies, design concepts, and models and their opportunities for improving sustainability. Since the application of sustainable development to urban planning and development in the early 1990s, many scholars and practitioners from different disciplines (urban planning, urban design, urban morphology, ecology, architecture, etc.) all have come to recognize and advocate that understanding and recalibrating the urban form and functioning of cities were crucial to developing a more sustainable urban future.

One strand of research on sustainable cities focuses on issues around the theory of sustainable urban planning (e.g. sustainable urban forms) and the effects of its application on cities. Typically, the sustainability of cities has been concerned with sustainability effects taking place within cities' boundaries (Höjer & Wangel, 2015). This pertains to the underlying theory of urban sustainability and its application as a foundation for urban practice (e.g. Williams, 2009), particularly in relation to eco–city (e.g. Girardet, 2008; Joss, 2011; Joss et al., 2013; Rapoport & Verney, 2011; Register, 2002; Roseland, 1997) and compact city (e.g. Hofstad, 2012; Jenks et al., 1996a,b; Neuman, 2005) as the most prevalent models of sustainable urban form (see, e.g., Jabareen, 2006; Kärrholm, 2011). The theory of sustainability has particularly been influential in how the subject of contemporary cities, in particular the built environment, has been studied and applied. As this theory is more normative, institutional, and philosophical, it is more open to re–interpretation, re–evaluation, or critical examination. Indeed, in urban practice not all the challenges and solutions pertaining to sustainable urban planning can be identified (Höjer & Wangel, 2015). And even the identified ones are usually not completely addressed and applied—urban problems are obviously of wicked sorts. In all, this strand of research is concerned with the implication of the theoretical underpinnings of sustainable urban planning, and to what extent this foundation delivers what is claimed. This entails questions aimed at challenging theoretical assumptions, discovering contradictions and weaknesses, identifying gaps and omissions, revealing fallacies, substantiating implications, and examining broad issues.

Remaining on the same strand of research and at the abstract and intellectual level, a large body of work tends to focus on the concepts and theories underpinning the thinking about the subject of sustainable city. This body includes analyzing discourses of urban planning and development and how decisions are made (e.g. Kumar & Pallathucheril, 2004; Portugali & Alfasi, 2008). Related issues pertain to the definition of theoretical terms and discursive notions as well as different understandings and constructions, and how these are germane to the subject of sustainable city (e.g. Bibri & Bardici, 2015; Dryzek, 2005; Hajer, 1995; Rapoport & Verney, 2011). This is because this subject has a theoretical base that is open to interpretation, evaluation, and examination, or in it, theoretical debate seems to be rife and a key aspect of the discipline of sustainable urban planning. Having a practical application, the subject of city within this discipline relies on theoretical assumptions and foundations. And it requires environmental, social, and economic issues to be addressed (e.g. Bulkeley & Betsill, 2005; Hofstad, 2012; McHarg, 1995; Register, 2002), as well as institutional priorities and technological considerations (e.g. Bibri & Krogstie, 2016a, 2017) to be set apart from theoretical matters of urban planning and development as internally consistent models or uniquely coupled with their distinct characteristics. In all, this research strand is concerned with comparing and evaluating concepts and approaches, weighing up arguments, rethinking issues, and challenging discursive assumptions—see examples relating to the topic of the social shaping dimensions of sustainable cities (Bibri & Krogstie, 2016a).

Another strand of research on sustainable cities entails a large body of analytical work. This academic endeavor focuses on investigating different propositions (models of problems and solutions) about what makes a city, or how it can be made, sustainable (e.g. Bibri & Bardici, 2015; Girardet, 2008; Hofstad, 2012; Jenks & Dempsey, 2005; Jabareen, 2006; Joss, 2011; Kärrholm, 2011; Neuman, 2005). Most of the analytical work carried out on sustainable cities entails exploring approaches to planning and development that combine various aspects of the city, including spatial organizations, urban infrastructures, urban environmental and management systems, ecosystem services, and green and energy efficiency technologies. A recent wave of this work involves sustainable initiatives that tend to focus on technical solutions (smart ICT) for making urban metabolism more efficient (e.g. Shahrokni et al., 2015). Here, urban metabolism as a framework serves to determine and maintain the levels of sustainability and health of urban forms, and thus its application is intended for sustainability reporting and urban design. From a general perspective, sustainable city development has, over the last two decades or so, emerged as a response to the challenge of sustainability. Accordingly, an array of the so–called models of sustainable urban form (e.g. compact city, eco–city, and new urbanism) has been developed to address the rising concerns about the environment, predominately. This is because the form of contemporary cities has been perceived mostly as a source of environmental problems (Alberti et al., 2003; Beatley & Manning, 1997; Hildebrand, 1999b; Newman & Kenworthy, 1989). However, of the existing models, compact city and eco–city have been seen as the preferred ones as to contributing to the goals of sustainable development (see, e.g., Hofstad 2012; Joss et al., 2013). Sustainable urban forms can be achieved by a combination of such typologies as density, compactness, diversity, and mixed–land use, supported by sustainable transport, ecological design, and solar passive design as design concepts, as well as advanced environmental and urban management systems (see Jabareen, 2006). Furthermore, several studies (e.g. Guy & Marvin, 2000; Joss, 2010; Jabareen ,2006; Kärrholm, 2011; Rapoport & Vernay, 2011) point to the issue of diversity with regard to the usages of the terms describing existing models of sustainable urban form, as well as that of the extent of convergence or divergence in the way in which different projects, initiatives, and plans pertaining to each model prescribe the approach into achieving that model, or conceive of how that model should look like. There is a great deal of heterogeneity among city initiatives or urban projects that are considered to be sustainable cities. This goes beyond their ambition to include their vision of what the future of sustainable urban development should entail. The alphabet soup of sustainable city projects and initiatives has generated a cacophony leading to an exasperating confusion in the field of sustainable urban development.

Whether in discourse, theory, or practice, the issue of sustainable urban forms has been problematic and difficult to deal with, and research results tend to be uncertain, weak, limited, divergent, and not conclusive, particularly when it comes to the contribution of these forms to the goals of sustainable development. i.e. the actual effects of the claimed benefits of sustainability (e.g. Bibri & Krogstie 2017; Jabareen, 2006; Kärrholm, 2011; Neuman, 2005). This points to the difficulty and uncertainty surrounding the translation of sustainability into the built form and thus its improvement. In this regard, according to Neuman (2005), conceiving cities in terms of forms remains inadequate to achieve the goals ascribed to the compact city; or rather, accounting only for urban form strategies to make cities more sustainable is counterproductive. Instead, conceiving these forms in terms of 'processual outcomes of urbanization' holds great potential for attaining the goals of sustainable development, as this involves asking the right question of 'whether the processes of building cities and the processes of living, consuming, and producing in cities are sustainable,' which raises the level of, and may even change, the game (Neuman, 2005). Townsend (2013) portrays urban growth and ICT development as a form of symbiosis. This entails a mutually beneficial relationship between ICT and urbanization (Bibri and Krogstie, 2017a). Besides, contemporary cities need to be dynamic in their conception, scalable in their design, efficient in their operational functioning, and flexible in their planning in order to be able to deal with population growth, environmental pressures, socio-economic need changes, unpredictable dynamics, and new trends. This perspective paves the way for a dynamic conception of urban planning that reverses the focus on urban forms governed by static planning tools, which is about processes rather than forms; this holds more promise in attaining the elusive goal of urban sustainability (Neuman, 2005). Durack (2001) argues for open, indeterminate planning due to its advantages, namely tolerance and value of topographic, social, and economic discontinuities; citizen participation; and continuous adaptation, which is common to human settlements like all other living organisms and systems. From a conceptually different angle, in urban planning and policy making, 'the concept of sustainable city has tended to focus mainly on infrastructures for urban metabolism—sewage, water, energy, and waste management within the city' (Höjer and Wangel, 2015, p. 3), thereby falling short in considering other urban systems and domains where smart solutions can have a substantial contribution in the context of urban sustainability. This concept has for long been promoted by systems scientists using the pragmatic framework for urban metabolism; as ICT-enabled evolution of this framework, smart urban metabolism is being implemented to overcome some of the limitations of urban metabolism (Shahrokni et al., 2015), which aims to sustain the levels of sustainability of urban forms. In fact, in light of the recent smart and sustainable city development (e.g Al Nuaimi et al., 2015; Batty et al., 2012; Bibri and Krogstie, 2017a,b; Kramers et al., 2014; Solanas et al., 2014), ICT solutions have been leveraged in the advancement of many aspects of urban sustainability. In all, there are several critical issues that remain unresolved and underdeveloped for applied purposes with regard to the extent to which the challenge of urban sustainability can be addressed, despite the promotion of sustainable cities as a desirable goal within planning contexts.

The debate over the desirable or ideal urban form continues, so does the evolvement of the concept of sustainable urban development as to developing more sustainable city models based on crafting new and making creative combinations of the typologies and design concepts of sustainable urban forms. Currently, such forms, in particular compact city, eco–city, and new urbanism, overlap in many aspects as to their visions, ideas, and concepts, although they entail some key differences in terms of design and planning tools (Jabareen, 2006; Bibri & Krogstie, 2017). This overlap can result in vast confusion in terms of conceptualizations, which in turn complicates the implementation of design and planning tools (see Nam & Pardo, 2011). Of pertinence to highlight here is that our study has a propensity to emphasize a mix of coherent, scalable, and dynamic typologies and design concepts together with relevant infrastructures and management systems. And in doing so, to look for a more comprehensive, extensible, and evolvable sustainable model of urban form—supported by advanced ICT enabled by the new wave of computing. This innovative approach has great potential to yield a more convincing and robust model of sustainable urban form. Indeed, it is important to shun looking for one–rule model among the existing ones by favoring certain typologies, design concepts (e.g. Kärrholm, 2011), and smart applications (e.g. Batty et al., 2012). The rationale is that it is potentially valid to argue in terms of several pathways, possibilities, combinations, and futures (see Guy & Marvin, 2000) in the case of considering matrices (see Jabareen, 2006 for an example of matrix) for the evaluation of the sustainability of existing models of sustainable urban form, or for combining smart solutions pertaining to certain urban domains. Our study departs from this perspective and hence postulates that there is no one single optimal or ideal sustainable urban form but diverse alternative forms whose discussion should normally 'follow a more heuristic [or exploratory] trajectory, addressing a plurality of important issues and methods, rather than producing one–rule models, one–liners or optimal solutions' (Kärrholm 2011). Important to note, indeed, is that existing urban forms differ as to their contribution to sustainability. In addition, as concluded by Jabareen, 2006, 'different. . .scholars may develop different combinations of design concepts [and typologies] to achieve sustainable development goals. They might come with different forms, where each form emphasizes different concepts.' Further and from a conceptually different angle, it is theoretically and practically of high relevance and importance in an increasingly technologized and computerized urban society to amalgamate the design concepts and typologies of sustainable urban forms with smart methods for the purpose of substantiating their practicality with regard to their contribution to sustainability, as well as to integrate them with smart solutions for the purpose of increasing their contribution to sustainability, in addition to evaluating to what extent they contribute to sustainability and identifying their untapped potential for achieving sustainability. See Bibri and Krogstie (2017) for more details about such perspectives. These suggestions should provide fertile insights into validating or rethinking the theoretical underpinnings of urban sustainability upon new evidence as to its effects in the context of sustainable urban forms. In our research endeavor, we aim to contribute to the existing work by extending and enhancing the studies being carried out in the field of sustainable cities. This can be accomplished by integrating the most sustainably productive typologies and design concepts with advanced ICT while taking scaling issues into consideration. For an overview of the scaling issues of sustainable urban forms, the reader is directed to Kärrholm (2011). The primary purpose of our scholarly endeavor is to advance urban sustainability with support of ICT of the new wave of computing given its enormous potential for improving urban operations, functions, designs, and services in terms of management and planning, as well as for providing flexibility for considering multiple spatial and temporal scales.

Towards this end, it is important to be cognizant that there should be no single off–the–shelf solution for making urban living more sustainable in a smart way, but a diversity of solutions should be available and encouraged—yet driven by a holistic approach into urban sustainability in terms of the integration of the established typologies and design concepts of sustainable urban forms, i.e. theoretically and empirically grounded and thus generally recognized and accepted urban strategies. Besides, feasible solutions must be adapted to the national or local context, and any urban development strategy must be based on the city's unique circumstances, capabilities, and ambitions. The diversity of solutions should primarily allow for informative or enlightening comparisons. The underlying premise is that since existing models of sustainable urban form have proven to contribute beneficially and differently to sustainability, a convergence on a theoretically and empirically grounded form—supported by the available ICT solutions and approaches—can be more valuable in terms of constructively guiding and directing future urban practices in terms of city functioning and planning—along the most desirable developmental path in an increasingly computerized urban society. This is what we are striving for as a primary goal of our study, that is developing a novel model of smart sustainable city of the future.

4.2.2. Urban sustainability frameworks: indicators and performance assessment tools

In the domain of urban sustainability, assessment frameworks are used to support decision–making in urban planning and development, as they entail methodologies and tools that sustainable cities rely on to show, evaluate, and improve their progress towards sustainability goals. There are many urban sustainability assessment frameworks in the literature. But we only cover and discuss the widely used and well–known performance measurement systems. Urban monitoring started in the early 1990s after establishing numerous (environmental) indicators to monitor sustainability of urban areas (Marsal-Llacuna et al., 2015), a few years after the widespread diffusion of the concept of sustainable development. The multiple indicators for measuring the quality of life appeared in the 2000s (Mercer 2014). Worth pointing out is that the explosion of indicators has been triggered by the multiplicity of interpretations of sustainable development and the widely varied approaches to its operationalization. However, urban sustainability indicators have been produced by environmental consultancy, sustainable capitalism, research, and green citizenship organizations (Ahvenniemi et al., 2017; McManus, 2012). Accordingly, urban sustainability assessment tools have been developed top–down by expert organizations. However, a number of scholars (e.g. Berardi, 2013; Robinson & Cole, 2015; Turcu, 2013) advocate the integration of citizen–led, participatory, and localized approaches. This is anchored in the underlying assumption that the relationships between urbanites, their activities, and the environment must be better understood in order to achieve the required level of sustainability in terms of the integration of its dimensions.

Sustainability indicators are used by public administration and political decision makers to confirm whether cities implement sustainable development strategies by enabling the assessment and monitoring of urban activities (Tanguay, Rajaonson, Lefebvre, & Lanoie, 2010). However, Huang, Yeh, Budd, and Chen (2009) note that they are associated with shortcomings, as they do not provide normative indications as to the direction to pursue, in addition to not reflecting systemic interactions. Furthermore, the performance assessment tools are intended for ranking sustainable cities or for allowing cities to find best practices and compare best solutions (Ahvenniemi et al., 2017). There exist diverse approaches to urban sustainability, thereby the diversity of performance assessment tools. In particular, a large number of environmental assessment tools have been developed for various urban domains. There are tools that measure the built environment, ranging from buildings to neighborhoods and districts, in addition to public transportation and services (Haapio, 2012). Well–known neighborhood sustainability rating tools (Sharifi & Murayama, 2013). Other assessment tools have been developed to help urban planners to assess the energy efficiency of a detailed city plan as regards to energy demand of buildings, transport systems, energy systems, and energy sources (Hedman, Sepponen, & Virtanen, 2014). Of importance to underscore is that existing sustainability performance assessment tools put a much stronger focus on environmental indicators (Berardi, 2013; Robinson & Cole, 2015; Tanguay et al., 2010) compared to social and economic indicators. For instance, the most well–known sustainable neighborhood rating schemes assign very low weight (about 3% for economy and 5% for well–being) to direct economic and social measures (Berardi, 2013). In addition, existing sustainable design approaches have been criticized for solely focusing on reducing harm to the environment (Cole, 2012; Reed, 2007). Consequently, Robinson and Cole (2015) have called for the more integrative and holistic concept of regenerative sustainability. Besides, cities should be seen as urban ecosystems that comprise interactions between the physical, social, and ecological components (Nilon, Berkowitz, & Hollweg, 2003). The physical component is associated with urban morphology (urban forms, spatial configurations, integration values, etc.), a field of study that is concerned with the spatial structures, organizations, and characteristic features of cities. The spatial distribution of activities, efficient use of resources, and accessibility of different services and facilities are crucial aspects of sustainable cities in terms of urban forms, operations, functions, and services, as well as their interconnections (Bourdic, Salat, & Nowacki, 2012; Salat & Bourdic, 2012).

4.2.3. Intellectual challenges

Sustainable urban forms for human settlements have been developed to meet the required level of sustainability by enabling the urban systems (built form, infrastructure, ecosystem and human services, and administration) and thus the urban domains to function in a constructive way. Seeking more convincing and robust models of these forms continues to be a significant challenge that motivate and induce scholars in different disciplines and practitioners in different professional fields to generate new ideas about, create new approaches into, and put forward new frameworks for redesigning, rearranging, and enhancing urban areas across multiple spatial scales, with the ultimate aim of achieving sustainability in terms of the integration of its dimensions. To develop a model of a high replicative capacity and seminal influence has simply been one of the most significant intellectual challenges for more than two decades. This implies that it has been difficult to translate sustainability into the built and infrastructural forms of contemporary cities, notwithstanding the importance of the topic of sustainability in urban research and planning. In addition, research, whether theoretical or empirical, tends to be scant on evaluating whether or the extent to which existing models of sustainable urban form contribute to sustainability or comparing different models according to their contribution to the goals of sustainable development. The very first endeavor in this direction was Jabareen, 2006 study, an attempt to develop a conceptual framework for assessing the sustainability of four urban forms: eco–city, compact city, new urbanism, and urban containment, and to articulate the underlying design concepts and principles. Still, although there appears to be in research on sustainable urban forms (e.g. Jabareen, 2006; Hildebrand, 1999a) and anthologies (Jenks & Dempsey, 2005; Williams et al., 2000) a consensus on topics of relevance to urban sustainability, it is not evident which of these forms are more sustainable and environmentally sound. Indeed, a critical review of existing models of sustainable urban form as approaches addressed on different spatial scales demonstrates a lack of agreement about the most desirable urban form in terms of the contribution to sustainability (see, e.g., Harvey, 2011; Tomita, Terashima, Hammad, & Hayashi, 2003; Williams et al., 2000). It is not an easy task to 'judge whether or not a certain urban form is sustainable' (Kärrholm, 2011). Even in practice, many planning experts, landscape architects, and local governments are—in the quest to figure out which of the existing sustainable urban forms is the most sustainable—grappling specifically with dimensions of these forms by means of a range of urban planning and design approaches (Jabareen, 2006). On the face of it, 'neither academics nor real–world cities have yet developed convincing models of sustainable urban form and have not yet gotten specific enough in terms of the components of such form' (Jabareen, 2006).

Furthermore, as hinted at above (performance assessment frameworks), sustainable urban forms tend to emphasize environmental or economic goals, and fall short in considering social goals (see, e.g., Bibri & Krogstie, 2016a; Jabareen, 2006). For instance, in the context of compact city, social and environmental goals continue to play second fiddle while economic goals remain at the core of planning (Hofstad, 2012). And in the realm of eco–city, the environmental dimension of sustainability is primarily linked to economic benefits and priorities, as the ambition of developing green and energy efficiency technologies is increasingly motivated more by economic values than by environmental gains (Bibri & Bardici, 2015). In short, environmental sustainability is viewed as a source of economic development. Besides, urban planners and policymakers are still, and will continue to, face difficult decisions about how they set priorities as to, and where they stand on, promoting economic development, protecting the environment, and fostering social equity in cities (Bibri & Krogstie, 2016a). The integration of sustainability dimensions is still of a loose kind at most, and is often associated with empty rhetoric, as economic aspects dominate in most instances. Nonetheless, there is an 'optimistic view that new procedures are likely to emerge and develop that strengthen the influence of social and ecological goals over urban planning and development practices'; regardless, to adopt sustainable development strategies and to reach sustainability can only 'occur through a sustained period of reflective thinking about existing societal models, accepting unavoidable changes, and confronting and resolving rather unshakable conflicts.' (Bibri & Krogstie, 2016a). In essence, the value of sustainability 'lies in the long–term goals of a socio–ecological system [human society within the biosphere] in balance: society strives to sustain the ecological system along with the economic system and social system. Hence, as a goal set far enough into the future, sustainability allows us to determine how far away we are from it and to calculate whether (and how) we will reach it.' (Bibri 2013).

4.3. Smart sustainable cities

4.3.1. On the emergence of the field

Not until very recently, smart sustainable urban development has attracted significant attention among contemporary urban scholars, planners, and policymakers. Its insertion, functioning, and evolution as a discourse and social practice is increasingly shaped and influenced by emerging ICT industry consortia, collaborative research institutes, policy networks, and 'Triple Helix of university–industry–government relations' (Etzkowitz & Leydesdorff, 2000) in terms of techno–urban innovation, not least in ecologically and technological advanced nations (Bibri & Krogstie, 2016a). While there is a growing interest in this flourishing interdisciplinary field of research, the academic discourse on smart sustainable urban development within the relevant literature is still scant—yet rapidly burgeoning. Indeed, very few studies (e.g. Bibri & Krogstie, 2016a; Kramers et al., 2014; Kramers et al., 2016; Rivera et al., 2015) exploring the subject of smart sustainable cities have been published in mainstream journals. The case is evidently different from smart cities and sustainable cities as urban development strategies, which have witnessed a proliferation of academic publications and thus varied emphases of research and a large body of practices. However, the speed at which the field of smart sustainable cities is gaining momentum and attracting attention gives a clear indication of its developmental path, flourishing nature, and future direction. In fact, this field of research comes as a natural pursuit within urban planning and development considering the unsolved and unsettled issues pertaining to existing models of sustainable city in terms of their contribution to sustainability, coupled with the deficiencies associated with the sustainability of existing approaches to smart city.

4.3.2. Research strands

The body of work available on smart sustainable cities thus far is evolving mainly out of theoretical, analytical, and overarching perspectives pertaining to smart cities and sustainable cities. One key strand of research tends to focus on combining aspects of existing sustainable city models and smart city approaches in an attempt to overcome the aforementioned issues relating to sustainability. Murray et al. (2011) maintain that a systemic integration of eco–city, knowledge city, and digital city as solutions for moving towards sustainability results in a smart urban planning approach. Batagan (2011) points out that this holistic approach holds potential to address the challenge of urban sustainability. Future research endeavors in this direction are expected to provide normative prescriptions for achieving the status of smart sustainable cities as well as to develop frameworks to measure this status. ITU (2014) provides a standardized basis for developing such frameworks. Thus far, there are many frameworks that can be used to measure either the smartness or the sustainability of the cities, as discussed above. In view of that, another strand of research concerns itself with developing integrated frameworks to measure the combination of these two urban constructs in the ambit of smart sustainable cities. Work in this area remains very scant due to the fact that the research is still in its infancy. There is no comprehensive framework in the literature that can tackle the dimensions of smart sustainable cities (Al-Nasrawi et al., 2015). In relation to this, Ahvenniemi et al. (2017) have attempted to develop an understanding of the commonalities and differences between the concepts of sustainable cities and smart cities as well as the related assessment frameworks by comparing 16 existing performance measurement systems (8 related to sustainable city and 8 related to smart city) with respect to 12 application domains in total and 3 impact categories of 958 indicators altogether. They conclude that there is large gap between smart city and sustainable city assessment frameworks with respect to sustainability. This supports the aim of our study in terms of integrating the ICT solutions of smart cities with the typologies and design concepts of sustainable cities to increase the contribution to the goals of sustainable development under smart sustainable cities.

Like the fields of smart cities and sustainable cities, the emerging field of smart sustainable cities is evolving into broad streams of scholarship, in addition to the above strands of research. One stream of scholarship is concerned with the theory of smart sustainable urban development and the effects of the combination of smartness and sustainability applications in contemporary cities, i.e. the implications of the practices of urban computing, urban ICT, and applied urban science for urban sustainability. The strand of work focused on the respective applications addresses questions around the role of smart solutions in catalyzing, boosting, and maintaining sustainable urban development processes, i.e. using advanced technologies to monitor, understand, probe, assess, and plan cities to improve sustainability (e.g. Bibri & Krgsotie, 2016a; Bibri & Krogstie, 2016b; Höjer & Wangel, 2015; Kramers et al., 2014; Kramers et al., 2016; Rivera et al., 2015). Smart solutions involve constellations of instruments encompassing sensing technologies, big data analytics, context–aware computing, cloud computing, and wireless communication networks and their use within diverse urban domains (e.g. transport, mobility, energy, environment, governance, healthcare, education, and safety). However, the current state of research in the realm of smart sustainable cities—a blossoming scholarly interdisciplinary field—shows that research is still in its early stages. Indeed, topical studies have typically focused on developing definitions and working with conceptualization and discursive issues (e.g. Bibri & Krogstie, 2016a; Höjer & Wangel, 2015; Rivera et al., 2015) to provide a joint understanding of this new techno–urban phenomenon and to serve as a ground for further discussions on what this evolving urban development strategy and techno–urban discourse aspire and claim to deliver in terms of smart sustainable urban planning. In addition, a part of the emerging analytical strand of research attempts to test some propositions (smart–urban solutions) about what makes a city smartly more sustainable. This line of work tends to be narrowly focused. For example, a recent study carried out by Kramers et al. (2014) addresses the topic of energy efficiency, i.e. using ICT solutions to reduce household energy use in cities, from an analytical perspective. While the authors focus solely on energy use, they did acknowledge that sustainability consists of interrelated environmental, social, and economic dimensions and concerns. Rivera et al. (2015) explore the potential of ICT to contribute to urban sustainability from a practice–oriented perspective in the context of smart sustainable cities, focusing more on discursive issues.

In addition, given the fact that sustainability is an integral part of some definitions of smart city, the concept of smart city has been used interchangeably with that of smart sustainable city, leading to confusion and misunderstanding in the urban domain. Some views might contend that 'the smart city is the smart sustainable city and that the word "sustainable" can be left out without further ado' (Höjer & Wangel, 2015). The different conclusions led to by recent studies (e.g. Kramers et al., 2013; Neirotti et al., 2014) on the integration of sustainability in smart cities can be explained by the gap between the theory and practice of smart cities. In contrast to the study carried out by Kramers et al. (2013), which shows that a few of smart city concepts include explicit objectives of environmental sustainability, the study conducted by Neirotti et al. (2014) indicates that environmental sustainability is explicit through the most common types of urban application domains being 'Natural Resources and Energy' and 'Transportation and Mobility' for smart city initiatives. Nevertheless, the key insight here is that the concept of smart city and what it entails in terms of smart applications holds some potential for sustainability—if astutely leveraged in the needed transition towards sustainable urban development. In other words, the concept of smart city provides solutions and approaches that can make sustainable cities smartly sustainable—if driven by a long–term planning approach that centers on sustainability. Colldahl et al. (2013) argue that the concept of smart city is a powerful approach to enabling cities to move towards sustainability.

Furthermore, a large part of research work on smart cities is currently focusing on a wide variety of technological propositions about what makes cities smart in terms of sustainability, efficiency, equity, the quality of life, or a combination of these. However, this relationship is too often, if not always, addressed separately from the rather established strategies through which sustainable urban forms can be achieved, namely density, diversity, compactness, mixed–land use, sustainable transport, ecological design, and passive solar design. Adding to this is the fact that the so–called smart technologies are sometimes used in cities without making any contribution to sustainability. For many contemporary urban scholars, theorists, and planners, these strategies are necessary to be adopted and implemented to achieve sustainability (see, e.g., Dumreicher, Levine, & Yanarella, 2000; Williams et al., 2000; Jabareen, 2006; Kärrholm, 2011)—irrespective of how intelligently other urban systems than the built form can be operated, managed, planned, and developed. ICT as an enabling and constitutive technology can indeed make substantial contributions in relation to these strategies. This involves not only catalyzing and boosting the development processes of sustainable urban forms, but also monitoring, understanding, probing, assessing, and planning these forms to advance their contribution to sustainability. Cities become smart sustainable when smart ICT is employed for making them more sustainable (Höjer & Wangel, 2015). How this can, or should, be accomplished is a question of what the body of research on both sustainable cities and smart cities suggests as to what is currently of priority, urgency, timeliness, and necessity to pursue as research endeavors in order to address the most critical issues around existing models of sustainable urban form using innovative solutions offered by advanced approaches to smart city. Another way forward is simply the adoption of the cutting–edge solutions being offered by smarter cities in terms of the underlying core enabling technologies and their novel applications and services for sustainability (Bibri & Krogstie, 2016a). It is argued that as data sensing, information processing, data analytics capabilities, and wireless communication solutions become deeply embedded into urban systems and urban domains and attached to everyday objects and citizens to address the challenge of sustainability, we can speak of sustainable cities getting smarter as to contributing to the goals of sustainable development more effectively and efficiently (Bibri & Krogstie, 2016a). However, regardless of the type of smart solutions proposed for sustainability, it is of critical importance to ensure smart initiatives resonate with the significant themes in debates on the typologies and design concepts of sustainable urban forms. Jabareen (2006) provides a detailed account of these themes. Bibri and Krogstie (2017) propose a matrix linking these themes with the applications being offered by ICT of the new wave of computing (UbiComp, AmI, the IoT, and SenComp) in the context of sustainable cities of the future.

4.3.3. *Scientific and intellectual challenges and environmental risks*

Smart sustainable cities of the future are most likely to involve the majority of the scientific and environmental challenges associated with smart cities of the future and some of the challenges pertaining to existing sustainable city models, at least in the short term. In this case, they will have to address and overcome these challenges in order to adhere—as a holistic approach to urban development—to the vision of sustainability. Here we focus on the challenges in relevance to our study. In this regard, the major scientific challenges to the development of smart sustainable cities encompass the following:

- To relate sustainable urban forms in terms of their typologies, infrastructures, management systems, ecosystem services, and human services to their operation, organization, coordination, planning, and development through monitoring, analysis, evaluation, management, control, and optimization, and what these entail in terms of modeling, intelligence, simulation, decision support, and prediction. In this respect, the efforts should be directed towards demonstrating how developments in big data analytics and context–aware computing and related infrastructures (data processing platforms, cloud computing infrastructures, and middleware architectures) can be integrated so to make these forms intelligently more sustainable in the way urban planners, urban administrators, and city authorities can use new technological applications, services, and capabilities for improving sustainability and integrating its dimensions.
- To explore the idea of sustainable urban forms as techno–urban innovation labs, which entails developing intelligence functions as new notions of the way these forms operate and be managed. These intelligence functions can, by utilizing the complexity and data sciences in developing advanced simulation models and optimization methods, allow the monitoring and design of these forms with respect to the efficiency of energy systems, the improvement of transport and communication systems, the effectiveness of distribution systems, and the efficiency of public and social service delivery. These intelligence functions can take the form of centers for scientific research and innovation with the primary purpose of continuously increasing the contribution of these forms to sustainability thanks to the possibility for building dynamic models of urban forms functioning in real time from routinely sensor–based/machine generated data.
- To construct and aggregate several urban simulation models of different situations of urban life pertaining to the way different urban domains within sustainable urban forms can be integrated and collaborate, as well as to how human mobility data can be linked to the spatial organizations, transport networks, mobility and travel behavior, socio–economic network performance, environmental performance, and land use, of these forms. Also to explore and diversify the approaches to the construction and evolution of urban simulation models. This is to inform the future design of sustainable urban forms on the basis on predictive insights and forecasting capabilities. This is increasingly becoming achievable due to the recent advances in, and pervasiveness of, sensor technologies and their ability to provide information about medium– and long–term changes in the realm of real–time cities.

Table 1
Discrepancies between smart and sustainable cities.

Discrepancies between Smart and Sustainable Cities
• Sustainable cities emphasize design concepts and principles and overlook smart solutions, and smart cities focus on modern ICT and efficient solutions and fall short in considering, if not ignore, design aspects. • Sustainable cities strive mainly for sustainability goals and smart cities mainly for smart targets. • Sustainability goals and smartness targets are misunderstood as to their interconnection. • Smart cities need to incorporate the goals of sustainable development and sustainable cities need to smarten up as to their contribution to these goals. • Sustainable cities need to leverage their informational landscape and smart cities their physical landscape in line with the vision of sustainability. • There is a misunderstanding of the link between the concepts of smart cities and sustainable cities. • There is a weak connection between the concept of smart cities and environmental sustainability. • Smart city assessment frameworks and concepts need to be redeveloped and redefined, respectively, in ways that incorporate the environmental indicators and theoretical constructs of sustainable cities. • Smart technologies are being used in smart cities without making any contribution to sustainability, and sustainable urban strategies are being applied without considering smart technologies.

- To improve different aspects of physical (and virtual) mobility using ICT of the new wave of computing in terms of big data analytics and context–aware computing, in particular in relation to such typologies as density, diversity, compactness, and mixed–land use by using both sustainable as well as efficient transport. Also to enhance spatial and non–spatial accessibilities to various job opportunities, public services, social services, and facilities in the context of sustainable urban forms.

As to the intellectual challenges, the practical use of the concept of smart sustainable cities requires the development and implementation of robust assessment methods and practices (indicators/metrics and their evaluation) to ensure that these cities are in fact (intelligently) sustainable (Höjer & Wangel 2015).This involves taking a holistic approach into evaluating the effects of ICT solutions on environmental sustainability (Bibri & Krogstie, 2016a). It is relevant to mention again that one of the significant challenges in the realm of sustainable cities is to develop and apply methods for identifying which kinds of solutions (combining design concepts, typologies, infrastructural systems, environment and urban management, environmental technologies, etc.) are needed, and also for evaluating the effects of these solutions in terms of their contribution to the goals of sustainable development based on a systemic perspective. Without evaluative approaches and practices, smart sustainable cities risk becoming no more than labels (see Höjer & Wangel, 2015), just like some sustainable urban forms becoming fallacies (e.g. Neuman, 2005)—without validated urban content or only for urban labelling (Bibri & Krogstie, 2016a).

In addition, the prospect of smart sustainable cities is increasingly becoming the new reality with the massive proliferation of data sensing, data processing, pervasive computing, and wireless networking technologies across urban environments. In other words, smart sustainable cities typically rely on the fulfillment of ICT visions of the new wave of computing. Consequently, it becomes inescapable to avoid the multidimensional effects ICT has on the environment. Due to the scale of its ubiquity presence and the massiveness of its use, future ICT has a number of risks and uncertainties in relation to environmental (and social) sustainability that need to be understood when placing high expectations on and marshaling colossal resources for developing, deploying, and implementing smart sustainable cities. There exist 'intricate relationships and tradeoffs among the positive impacts, negative effects, and unintended consequences for the environment' (Bibri, 2015b), flowing mostly from the design, development, use, application, and disposal of UbiComp, AmI, the IoT, and SenComp technologies throughout smart sustainable cities. As argued by Krogstie 2016a, p. 26), 'it is difficult to estimate the potential of ICT for environmental sustainability in a. . .meaningful way in the ambit of smart sustainable cities, as advanced ICT solutions involve technological innovation systems embedded in much larger socio–technical systems in which a web of factors and actors other than merely scientific and technical potential come into play. . . ICT...own emissions are increasing due to the growing demand for its advanced applications and services being offered by UbiComp, AmI, the IoT, and SenComp. . . The adverse environmental effects of new technologies are multidimensional, complex, and intricate.' They include constitutive effects, rebound effects, indirect effects, direct effects, and systemic effects. For a detailed account and discussion of these effects, the reader is directed to Bibri and Krogstie (2016a). Again, it is very challenging, if not daunting, to evade the conflicts among the goals of sustainable urban development. Brown (2012) argues that sustainability science must involve the role of technology in aggravating the unsustainability of social practices (e.g. urban planning and development), just as in tackling the complex problems these practices generate. In all, unless smart sustainable cities can 'be reoriented in a more environmentally sustainable direction, as [they] can not, as currently practiced, solve the complex environmental problems placed in [their[agenda' (Bibri & Krogstie, 2016a), they risk becoming fallacies in the long term. ICT solutions should in this regard be carefully implemented in conjunction with other measures as well as policy and planning instruments to yield the desired outcomes as to the environmental gains and benefits expected to result from the development and implementation of smart sustainable cities of the future. Towards this end, it is important to underscore from the perspective of smart sustainable urban development that for advanced ICT solutions to function constructively, a concerted action is required, which should be guided by a coordinating body with relevant roles and competences in order to strategically assess the implications of ICT investments in this direction (see Höjer & Wangel, 2015), and thereby steer ICT innovations in ways that align with the goals of sustainable urban development towards achieving the long–term goals of urban sustainability within ecologically and technologically advanced nations (Bibri & Krogstie, 2016a).

4.3.4. Key discrepancies between smart cities and sustainable cities

Here we outline key discrepancies (a lack of compatibility) (see Table 1) between smart cities and sustainable cities as regards to enhanced levels of sustainability. This is intended to inspire or stimulate further scholarly or academic inquiry into the area of smart sustainable urban planning and development.

5. Research opportunities and horizons for smart sustainable cities of the future

5.1. Prospective inquiry avenues and endeavors: a research–Inspired applied theoretical inquiry

It is important to underscore that the emerging field of smart sustainable cities is a fertile area of interdisciplinary scholarly inquiry, entailing clearly a wide spectrum of opportunities, horizons, and endeavors, with many intriguing questions and multifaceted phenomena awaiting scholars and practitioners in different disciplines. This is underpinned by the recognition by research community that the concept of smart sustainable city holds great potential to enable urban environments to function sustainably in a more constructive way than at present. Its main strength lies in the high influence it will have on many domains of contemporary cities and what this entails in terms of sustainability and the integration of its environmental, social, and economic dimensions. This is coupled with the unique opportunity to take stock of and harness the plethora of the lessons learned from more than two decades of research and planning devoted for seeking and implementing sustainable urban forms, and how to apply this together with the most advanced ICT solutions to the sustainability challenge of our time, which is the success of the goals of sustainable development. Therefore, it is high time to leverage the theoretical and substantive knowledge accumulated hitherto on smart sustainable urban development through recent research endeavors that can contribute to make urban living smartly more sustainable—i.e. with support of ICT of the new wave of computing in terms of what it has to offer as innovative solutions and sophisticated approaches directed for improving sustainability.

The research opportunities currently available within the field of smart sustainable urban development are vast, ranging from applied theoretical studies, to theoretical development studies, to exploratory studies (e.g. Al-Nasrawi et al., 2015; Ahvenniemi et al., 2017), to empirical studies (e.g. Kramers et al., 2016; Shahrokni et al., 2015), to analytical studies (e.g. Kramers et al., 2014), and to discursive and institutional studies (e.g. Bibri & Krogstie, 2016a; Rivera et al., 2015). Of these studies, research endeavors within or towards theoretical development for the purpose of application remains scant (little or no)—yet of utmost relevance and importance at this stage of research within smart sustainable cities—as it is still in its infancy. This is primarily to contribute to laying the foundations for future urban practices in terms of the smart form of sustainable development. While this can take various forms to achieve, previous urban research on sustainable urban forms (e.g. Girardet, 1999; Gibbs, Longhurst, & Braithwaite, 1998; Jabareen, 2006; Jenks et al., 1996a,b; Nijkamp & Perrels, 1994; Register, 2002; Roseland, 1997; Wheeler, 2000; Williams et al., 2000) shows that seeking models of these forms, or putting forward new frameworks for the restructuring and redevelopment of urban environments across several spatial scales to achieve sustainability, was of prime focus during the inception and application of sustainable development into urban planning. This also applies, to some extent, to early research within the field of smart cities (e.g. Giffinger et al., 2007). In view of that, following this research path in the context of smart sustainable cities is deemed of high pertinence and thus more encouraged at this stage of research, or generally when it comes to the emergence of new urban development strategies. Our research pursuit is indeed in the spirit of the way sustainable cities, in particular, as complex systems have actually materialized and evolved into established models of sustainable urban form. Any research endeavor in this direction should make best use of what has been done with regard to the accumulated knowledge in the field of sustainable cities as well as in that pertaining to smart city approaches that explicitly incorporate the goals of sustainable development. Of equal importance in this respect is to attempt to take into account what has been criticized in the context of sustainable cities and smart cities in terms of deficiencies, uncertainties, fallacies, paradoxes, and misunderstandings regarding the development of smart sustainable cities of the future. Overall, it is deemed of high relevance to develop, using the relevant scales of design concepts and topologies of sustainable urban forms in conjunction with smart technologies and their novel applications, a theoretically and practically convincing model of smart sustainable city or a framework for strategic smart sustainable urban development.

Table 2
Existing gaps in the research within the field of smart sustainable cities.

Existing Gaps in the Research within the Field of Smart Sustainable Cities
• There is a need for applied theoretical grounding for providing an explanation of and a basis for the potentially increased contribution of smart sustainable urban form to the goals of sustainable development.
• There is a need for integrated models for spurring the practice of the development and deployment of smart sustainable cities.
• There is no framework to be used as a classification system or ranking instrument against which smart sustainable cities can be evaluated in terms of their smart contribution to sustainability.
• There is no assessment framework for measuring how smartness enhances sustainability and vice versa.
• The is no theory building attempts in respect of the integration of sustainable city models and smart city approaches.
• There is a paucity of research on conceptual and theoretical models for smart sustainable cities.
• There is no comprehensive model for merging the informational and physical landscapes of smart sustainable cities.
• There is a need for a holistic and shared model of smart sustainable city given the systematic perspective on and the universal character of sustainability.
• There is no common conceptual framework for comparing the evolving models of smart sustainable city and planning propositions.
• There is a need for theory for evaluating whether and the extent to which a given model of smart sustainable city contributes to sustainability.
• There is a need for theory for comparing potential models of smart sustainable city according to their contribution to sustainability goals and smartness targets as an integrated approach.
• There is a weak connection between the concept and development of sustainable cities and smart cities.
• There is a need for approaches into applying smart ICT as a constitutive technology to further enhance the contribution of the typologies and design concepts of sustainable urban forms to sustainability.
• There is need for combining the typologies and design concepts of sustainable urban forms with smart methods to evaluate their practicality with regard to their contribution to sustainability.
• Sustainable cities remain inadequately scalable in design and flexible in planning without support of smart solutions in response to urban growth, environmental pressures, and changes in socio–economic needs.
• There is a need for providing normative prescriptions for achieving the status of smart sustainable cities and for developing assessment frameworks for measuring and improving this status.
• There is a lacuna in analytical studies for testing propositions about what makes a sustainable city smartly more sustainable.
• There is a lack of conception of sustainable urban forms in terms of processual outcomes of urbanization, which is inextricably linked to smart ICT.
• Sustainable cities still focus mainly on infrastructures for urban metabolism, and fall short in considering several urban domains where smart solutions can have substantial contributions in relation to sustainability.

5.2. *Towards an integrated approach into smart sustainable urban form: justifications and beyond*

In light of the above, a worthy and pertinent research endeavor to engage in is to develop an integrated approach into smart sustainable urban form that can have academic buy–in and practical relevance in relation to the future form of smart sustainable urban planning and development. The rationale for this research pursuit is manifold. To begin with, theoretical development has been notably slow in respect of sustainable city models as to their integration with smart city approaches. Moreover, there is a need for applied theoretical grounding that can provide an adequate explanation of and a strong basis for the potentially increased contribution of smart sustainable urban form to the goals of sustainable development given that the research in the field is still in its early stages, and therefore there is a need for integrated frameworks to spur the practice of the development of smart sustainable cities (or urban forms). Additionally, there has been no attempt to develop any framework for smart sustainable urban form to be used as a classification system or ranking instrument against which existing and new smart sustainable cities can be evaluated in terms of their contribution to sustainability. Even in relation to sustainable cities, although existing sustainable urban forms are conceptually diversified and strategically nuanced, theoretical foundations and lineages seem to be in practice disregarded, and distinctions among or comparisons between models are less significant, while pragmatic concerns are more prominent and tend to prevail in urban projects and initiatives (see, e.g., Jabareen, 2006; Kärrholm, 2011; Rapoport & Vernay, 2011). In particular, common conceptual or integrative frameworks for comparing sustainable city models and planning propositions are very scant. For instance, there is a lack of theory that can assess whether and the extent to which existing models of sustainable urban form contribute to sustainability or contrast their variations based on their contribution to the goals of sustainable development, to iterate. A number of other questions has arisen from the existing body of research work on sustainable urban forms reviewed above that deserve more attention and motivate new research in the applied theoretical direction—in addition to questions involving the integration of sustainable city models and smart city approaches. One major critique of the literature on sustainable urban forms and smart cities is that it tends to be heavy on speculation and light on theoretical development and applied theoretical studies—existing design concepts and principles pertaining to these forms and emerging ICT applications for smart cities have inadequate explanatory power, especially with regard to their combination in a given city model—as well as light on empirical evidence concerning the same facet. Regardless, sustainable and smart cities tend to present ideals, and much of what they claim in the context of sustainability remains still at the level of discourse (e.g. Batty et al., 2012; Hofstad, 2012; Roseland, 1997). The same in fact goes for smart sustainable cities at the current stage of their conceptualization and vision (e.g. Bibri & Krogstie, 2016a). Adding to this is that existing models of sustainable urban form as to the underlying design concepts and typologies tend to be static and fail to account for changes over time. Whereas a well–established fact is that cities evolve and the knowledge underlying their design and planning is perennially changing. Conceiving urban forms as 'processual outcomes of urbanization' pave the way for dynamic conception of urban planning that reverses the focus on urban forms governed by static planning tools (Neuman, 2005), to iterate. Here ICT is of high significance given its symbiosis character with urbanization. This dynamic conception become even of critical importance when including ICT in the equation—because ICT develops rapidly due to the pace of innovation in computing—as to its integration with the design concepts and typologies of sustainable urban forms. Smart sustainable cities of the future need to be scalable in design and flexible in planning as to their functioning and management as a way to respond to urban growth, environmental pressures, and changes in socio–economic needs. Indeed, at the core of smart sustainable cities of the future is the conception of building and using urban dynamic and simulation models and intelligence functions that adapt to the changing and evolving urban forms and the underlying urban systems and domains as well as their evolution.

5.3. A comprehensive list of the gaps in the research within the field of smart sustainable cities

On the basis of our analysis and discussion done in the previous sections, we present here a comprehensive list of the existing gaps in the research within the field of smart sustainable cities (see Table 2). This list includes the key gaps that we aim to address in our study based on an applied theoretical approach. As for the other gaps, they constitute potential research directions. They are therefore meant to encourage scholars in the field of smart sustainable cities to pursue theoretical, applied theoretical, exploratory, analytical, empirical, discursive, and futuristic inquiries.

5.4. Major advantages of smart and sustainable cities

We now present a tabulated version of our analysis with respect to the major advantages of smart and sustainable cities (see Tables 3 and 4). The purpose is to provide insights into understanding the relevance and meaningfulness of merging and harnessing the strengths of smart and sustainable cities into an integrated approach for applied purposes as to future practices in the area of smart sustainable urban planning and development. This can be accomplished by developing a model that entails smartening up existing models of sustainable urban form through integrating the most sustainably sound typologies and design concepts of these models with the most advanced solutions and approaches of smart cities in light of ICT of the new wave of computing.

6. Future urban planning practices and emerging scientific and technological trends

6.1. Unprecedented changes in urbanism and sustainable urban planning

The recent wave of smart sustainable urban planning is heralding major changes in the context of urbanism and sustainability.

Table 3
Major advantages of smart cities.

Advantages of Smart Cities
• Smart and data–centric applications for enhancing the contribution of the typologies and design concepts of models of sustainable urban form to the goals of sustainable development. • Sophisticated data–centric methods for evaluating and substantiating the practicality of these typologies and design concepts as to their contribution to these goals. • Data–centric techniques for comparing different models of sustainable urban form as to their contribution to these goals. • Effective models for urban design scalability, urban functioning efficiency, and urban planning flexibility necessary for responding to urban growth, environmental pressures, and changes in socio–economic needs. • Advanced tools and methods for realizing a dynamic conception of models of sustainable urban form in terms of processual outcomes of urbanization. • Smart frameworks for smartening up the metabolism of models of sustainable urban form. • Smart applications for integrating and enhancing urban systems and facilitating collaboration among urban domains in the context of models of sustainable urban form. • Relating the typologies and design concepts of models of sustainable urban form to their operational functioning and planning through monitoring, analysis, management, control, and optimization. • Exploring the idea of models of sustainable urban form as techno–urban innovation labs. • Constructing and aggregating several urban simulation models of different situations of urban life. • Diversifying modeling approaches into building urban simulation models to inform the future design of models of sustainable urban form on the basis of predictive insights and forecasting capabilities. • Improving participation, equity, fairness, safety, mobility, and accessibility. • New ways of understanding and addressing urban problems and challenges. • Identification of all kinds of urban risks, uncertainties, and hazards in models of sustainable urban form.

Table 4
Major advantages of sustainable cities.

Advantages of Sustainable Cities
• Theoretically and practically grounded urban strategies for achieving the required level of sustainability. • Approaches into applying the knowledge of urban sustainability and environmental technologies to the planning and design of cities. • Sustainable development strategies for fostering advancement and innovation in urban infrastructures and their operational functioning, management, and planning, as well as in natural resources management. • Established methods for maximizing energy efficiency, lessening pollution and waste levels, and improving human life quality and well–being. • Best practices of successful implementation of sustainably sound typologies and design concepts. • Advanced knowledge on models of sustainable urban form in terms of different spatial levels: regional and metropolitan levels, city level, community level, neighborhood level, and building level. • Different combinations of density, compactness, diversity, mixed–land use, sustainable transport, ecological design, and passive solar design, with different levels of performance and contribution as to sustainability. • Successful practices of ecological diversity, green technology, integrated renewable solutions, and environmental management. • Advanced frameworks for efficient metabolism. • Practices of renewable energy, zero–waste, and carbon–neutral neighborhoods and districts. • Environmental, social, institutional, and land use policy instruments for sustainably managing urban spaces.

The research and practice in the field of smart sustainable cities tends to focus on the identification of the urban domains that are associated with sustainability dimensions (such as transport, energy, environment, mobility and accessibility, public and social services, and public safety)—on the basis of big and context data—for further analysis, interpretation, reasoning, and modeling to develop and employ urban intelligence and simulation models for strategic decision–making purposes pertaining to sustainability (Al Nuaimi et al., 2015; Batty et al., 2012; Bibri & Krogstie, 2016b), among other things.This also involves how these domains interrelate and affect one another in relation to particular organized and coordinated physical arrangements and spatial organizations. In light of this, urbanism (the way of life characteristic of cities) has become as much a function of sensed, processed, analyzed, modeled, simulated, and networked urban data as it is of an organized, coordinated, and standardized physical arrangement of the city and the underlying infrastructural systems, processes, functions, and services in terms of management, planning, and development (e.g. Batty et al., 2012; Batty, 2013a,b; Bibri & Krogstie 2016a,b; Böhlen & Frei, 2009). Accordingly, the concept and development of smart sustainable cities entail thinking about and conceiving of urban environments as constellations of instruments across spatial and temporal scales that are networked in multiple ways to provide continuous data coming from urban domains, employing pervasive sensing, processing, and networking technologies, in order to monitor, understand, and analyze how cities function and can be managed so as to guide and direct their development towards sustainability. Therefore, the urban ICT enabled by the new wave of computing is drastically changing the way cities can be planned across many spatial scales and over multiple time spans, combining both short–term and long–term decision–making strategies (see Batty, 2013a). One implication of this is that cities are getting smarter in their endeavors to achieve the required level of sustainability. The technical features of smart sustainable urban planning involve the application of advanced ICT as a set of scientific and technical processes to land use patterns, natural ecosystems, physical structures, spatial organizations, natural resources, infrastructural systems, socio–economic networks, and citizens' services. Recent evidence (e.g. Al Nuaimi et al., 2015; Batty et al., 2012; Bibri & Krogstie, 2016a; Kramers et al., 2014; Neirotti et al., 2014; Shahrokni et al., 2015) lends itself to the argument that an amalgamation of these strands of urban planning with ICT can help create more sustainable and thus livable and attractive cities. In all, the smart approach to planning is of fundamental importance for strategic sustainable urban development, which is necessary for achieving the long–term goals of urban sustainability. Besides, the functioning, management, and organization of urban systems, processes, and activities in the field of sustainable urban planning require not only complex interdisciplinary knowledge of sustainability, but also sophisticated technologies and powerful computational and data analytics capabilities.

6.2. Evolving and upcoming shifts in city approaches and models driven by data science

The evolving smart approach to sustainable urban planning and development has materialized as a result of the recent shifts in city approaches—from digital city, intelligent city, networked city, knowledge city, information city, and so on to smart cities, and from smart cities to smarter cities, namely ubiquitous city (e.g. Lee et al., 2008; Shin 2009), sentient city (e.g. Shepard, 2011; Thrift, 2014), ambient city (e.g. Böhlen & Frei, 2009; Crang & Graham, 2007), and city of an Internet of everything (e.g. Kyriazis et al., 2014). Another yet evolving shift is from smart and smarter cities to more hybrid forms of cities, such as eco—knowledge city. energy–efficient city, real—time sustainable city, sustainable ubiquitous city, and so on, which all constitute instances of smart sustainable cities. Worth noting in the event of these shifts is that ICT as technological applications of recent scientific innovations in computing has been evolving just as the underlying knowledge of how to understand technological systems and the way in which they can be applied in and transform society (in better ways) are evolving. This is predicated on the assumption that 'science–based technology develops dependently of society, in a mutual shaping process where they both are shaped concurrently and thus affect each other and evolve. In other words, science and technology. . .shape and influence society and vice versa.' (Bibri 2015b). The underlying premise is that technological systems and applications as a form of scientific knowledge are embedded in the wider social context within which they arise (see Bibri & Krogstie, 2016a). The social conditions as structures and processes affect scientific knowledge and activity (Joseph & Sullivan, 1975), and vice versa. Social studies of science demonstrate that scientific knowledge and related system of production are shaped by the wider social context in which scientific inquiries and endeavors take place (Latour, 1987; Latour & Woolgar, 1986). These theoretical perspectives are of relevance to smart sustainable cities as a form of scientific knowledge, which arises from and is embedded in the wider social context. As reported by Bibri and Krogstie, 2016a, smart sustainable cities 'are mediated by and situated within ecologically and technologically advanced societies. And as urban manifestations of scientific knowledge and technological innovation, they are shaped by, and also shape, socio–cultural and politico–institutional structures.'

Furthermore, data sensing, processing, analysis, modeling, and simulation (as elements of data science) are generating radical shifts in many sciences in the information age, whether in relation to the city or other venues in modern society, such as complexity science, applied urban science, environmental science, green chemistry, sustainable development engineering, and sustainability science, as well as in the way these sciences can potentially be combined into new sciences. Speaking of the information age, the conception of smart sustainable cities epitomizes a product of a shift from a world based on energy and materials to a world increasingly grounded in information and its manipulation. In this regard, many scholars in different disciplines (e.g. Al Nuaimi et al., 2015; Batty et al., 2012; Bibri & Krogstie, 2016b, 2017; Böhlen & Frei, 2009; Kramers et al., 2014; Shahrokni et al., 2015; Shepard, 2011) advocate the inclusion of ubiquitous sensing, computing, and wireless networking technologies into urban planning and development as a core feature of smart (and) sustainable cities of the future. This is marking the next wave of urban analytics, of which big data constitute a fundamental ingredient. Indeed, as citizens and other urban entities increasingly emit spatial and urban data through their use of various technologies, coupled with data science becoming a more accessible tool on a wide–city scale, more extensive data can potentially allow urban departments, city administrators, and city authorities to monitor, understand, probe, and respond to such factors as mobility, accessibility, transport, energy, public safety, healthcare, public feedback, and so on in a real–time fashion. Obviously, new urban conditions require new urban planning approaches, especially traditional urban planning approaches alone are no longer of pertinence in terms of effectively operating, managing, organizing, evaluating, and planning cities.

The traditional model of the city, which is founded on the idea of the city as being a stable or constant structure, is rapidly changing, so too are the associated planning approaches in response to the emerging shifts brought by computing and ICT, underpinned by their foundation on the complexity and data sciences: from focusing on physical and spatial development to including broader principles (e.g. sustainability) and relying on big data analytics, context information processing, intelligence functions, and simulation models, and what these entail in terms of sensing, computing, data processing, and wireless networking technologies. The basic idea is that the traditional city model can no longer handle current planning conceptions and address emerging challenges in an increasingly technologized and computerized urban world—pervaded with computer technology and dominated by computable information that leaves no physical traces and has no spatial aspects in terms of area, position, location, and shape. As supported by Batty et al. (2012), the city planning systems currently in use 'are not fit–for–purpose', and hence the shifts that need to be instigated are the kind of unprecedented paradigm changes. This entails, in the context of smart sustainable cities, the development, deployment, and coordination of ICT infrastructures, applications, and services and the underlying distributed and heterogeneous environments in terms of sensing, stream processing, cloud computing, and wireless networking on city–wide scale for a wide connectivity, accessibility, and use for relevant urban entities, as well as for collective intelligence functions and service delivery systems. Adding to this is the use of advanced techniques of big data analytics capable of handling billions of observations, transactions, and interactions for discovering new knowledge necessary for managing and planning cities and redesigning existing ones. Other paradigm changes encompass devising a new science of socio–spatial behavior and enabling existing non–digital technologies to merge and co–exist with digital technologies in an integrated fashion (Batty et al., 2012). In all, the way in which cities are understood and conceptualized has drastically changed: from being viewed as closed and static systems to being seen as complex, dynamic, adaptive, and evolving systems in terms of their behavioral patterns and internal and external interactions.

6.3. The next wave of city analytics and computing for urban sustainability

It is worth mentioning that the next wave of urban analytics and computing is associated with smarter cities (smart cities of the future) as well as smart sustainable cities of the future, which both rely on the fulfillment of ICT visions of the new wave of computing with the purpose of achieving smart targets and sustainability goals, respectively.

6.3.1. ICT of the new wave of computing: big data analytics and context–aware computing

Cities as complex systems, with their domains becoming more interconnected and their processes highly dynamic, rely more and more on sophisticated technologies to realize their potential for responding to the challenge of sustainability. The most prevalent and influential of these technologies are big data analytics and context–aware computing. These are rapidly gaining momentum and generating worldwide attention in the realm of smart sustainable urban development (e.g. Al Nuaimi et al., 2015; Batty et al., 2012; Bibri & Krogstie, 2016b; Solanas et al., 2014). Moreover, context—aware behavior and big data capability are prerequisites for realizing the next generation of ICT and their applications (e.g. Batty et al., 2012; Bibri & Krogstie, 2016b; Böhlen & Frei, 2009; Coutaz, Crowley, Dobson, & Garlan, 2005; Schmidt, 2011; Riva, Vatalaro, Davide, & Alcañiz, 2008; Solanas et al., 2014; Shepard, 2011; Vongsingthong & Smanchat, 2014). In this regard, big data trends are mainly associated with the IoT technology (e.g. Bibri and Krogstie, 2017; Batty et al., 2012; Vongsingthong and Smanchat, 2014) and context data trends with AmI and SenComp (in addition to UbiComp) technologies (e.g. Bibri and Krogstie, 2017; Böhlen and Frei, 2009; Shepard, 2011; Solanas et al., 2014), with some overlaps among both these trends as well as technologies. Of importance to underscore is that the IoT is a form of UbiComp, and AmI and SenComp are two ICT visions that imply a slightly different focus in terms of the concept of context as to its elements (e.g. Bibri and Krogstie, 2016a). Indeed, UbiComp and the IoT tend to deal with more physical objects and thus involve more sensors than AmI and SenComp due to the scale of their ubiquity, and hence the volume of the data generated is huge and the processes and infrastructures involved in handling these data are complex. Moreover, UbiComp and the IoT involve complex sensor infrastructures and networks for the objects involved are numerous and boundless. (Bibri and Krogstie, 2017a). However, in the near future, the core enabling technologies of UbiComp, the IoT, AmI, and SenComp, which involve big data analytics and context–aware computing and what these entail in terms of digital sensing technologies, cloud computing infrastructures, middleware architectures, and wireless communication networks, will be the dominant mode of monitoring, understanding, analyzing, assessing, operating, organizing, and planning smart (and) sustainable cities to improve their contribution to the goals of sustainable development. Big data analytics and context–aware computing as rapidly growing areas of ICT are becoming important to the functioning, planning and development of smart sustainable cities (Bibri & Krogstie, 2016b). Therefore, the expansion of these computing approaches are increasingly stimulating the development of smart sustainable cities as urban initiatives and projects. Besides, big and context data constitute fundamental ingredients for the next wave of urban analytics and computing.

6.3.2. Opportunities and applications of big data analytics and context–aware computing

The notion of big data and its application in urban analytics have attracted enormous attention among various urban scholars and practitioners over the past few years. The big data paradigm is fundamentally changing the way cities function and can be managed (e.g. Batty, 2013a,b; Bibri & Krogstie, 2016b). Unquestionably, the main strength of big data lies in the high influence it will have on many facets of smart sustainable cities and their citizens (e.g. Al Nuaimi et al., 2015; Batty et al., 2012; Bibri & Krogstie, 2016a,b; Khan et al., 2015; Pantelis & Aija, 2013). Today, a large part of ICT investment from large technology companies like IBM, Oracle, Microsoft, SAP, and CISCO is being funneled into and directed towards how to process, analyze, manage, model, and simulate big data. In parallel, research on big data is very active in many universities and research institutions across the globe.

Context–aware computing constitutes a key component of the infrastructures of smart sustainable cities (e.g. Bibri & Krogstie, 2016b; Kamberov, 2015; Solanas et al., 2014) and future cities (e.g. Riva et al., 2008). Local city governments are investing in advanced ICT to provide technological infrastructures supporting AmI and UbiComp, as well as to foster respect for the environmental and social responsibility (e.g. Solanas et al., 2014). Hence, there are many opportunities for smart sustainable cities to embrace from the use of context–aware technologies due to the role they will play in several important areas, including energy, environment, education, healthcare, utility, and public safety (e.g. Batty et al., 2012; Bibri & Krogstie, 2016b; Böhlen & Frei, 2009; Shepard, 2011; Solanas et al., 2014).

The use of big data analytics and context–aware computing as a set of sophisticated techniques, methods, and technologies offers the prospect of smart sustainable cities in which natural resources can be managed safely, sustainably, and efficiently in a smart way to improve societal and economic outcomes. Indeed, significant opportunities exist for these two technologies in relation to transforming the sustainable urban model. This is due to that the range of urban application areas that utilize big data analytics and context–aware computing in connection with sustainability is potentially huge, as these two advanced forms of ICT usher in computing and analytics in nearly all urban domains. Among these applications the following is included (e.g. Bibri and Krogstie 2016a):

- Healthcare and social support
- Learning, education, and tele–working
- Public safety and civil security
- Energy efficiency and management
- Environmental monitoring and protection
- Transport efficiency and management
- Water and waste management
- Mobility and accessibility effectiveness
- Urban infrastructure monitoring and management
- Medical and health systems
- Natural ecosystems
- Traffic management and street light control
- Strategic planning and efficient design

In other words, the key smart applications enabled by big data analytics and context–aware computing include smart transport, smart energy, smart environment, smart planning, smart design, smart grid, smart traffic, smart education, smart healthcare, and smart safety (Bibri & Krogstie, 2016b). Therefore, the opportunities for the development and deployment of the innovative solutions offered by ICT of the new wave of computing are tremendous—if it can be directed towards urban sustainability and its investment be justified by environmental concerns and socio economic needs in terms of unlocking the potential and exploiting the benefits of big data analytics and context–aware computing in the realm of smart sustainable cities. As argued by Bibri and Krogstie (2016b, p. 1), 'combining big data analytics and context–aware computing could be leveraged in the advancement of urban sustainability, as their effects reinforce one another as to their efforts for transforming urban life in this direction by employing and merging data–centric and smart applications to enhance, harness, and integrate urban systems as well as facilitate collaboration and coupling among diverse urban domains.'

6.3.3. Research gaps and scientific challenges

The bulk of work relating to the recent increase of research in big data analytics and context–aware computing in the area of urban planning and development is associated with scattered and small research programs and projects. And it lacks comprehensive and large–scale initiatives. Also, while these two advanced technologies cover multiple application domains (e.g. Al Nuaimi et al., 2015; Batty et al., 2012; Bibri & Krogstie, 2016b), it is undeniable the disproportionate weight of a relatively small number of urban domains in setting the research agenda. In relation to big data analytics, many sustainability issues have not yet been effectively addressed, including public health, energy, environment, disaster forecasting, water resources, and biodiversity (DeRen et al., 2015). In addition, there are important questions that are largely ignored concerning the link between the urban domains associated with sustainability and the typologies and design concepts of sustainable urban forms. These questions pertain to the key themes in debates on density, compactness, diversity, mixed–land use, sustainable transport, and ecological design, as well as to the ability of monitoring, probing, and planning sustainable urban forms in ways that strategically evaluate and improve their contribution to the goals of sustainable development (Bibri & Krogstie, 2017). Moreover, there are issues that are barely explored to date regarding how the urban domains operating within sustainable urban forms can be integrated and coordinated to facilitate collaboration among them in terms of operations, functions, and services for advancing sustainability (see Bibri & Krogstie, 2016b).

The rising demand for big data analytics and context–aware computing as disruptive technologies presents significant scientific and intellectual challenges that need to be addressed and overcome as to the design, development, and deployment of data–centric and smart applications within smart sustainable cities. These challenges are mostly computational and analytical in nature, including constraints of design science and engineering (e.g. Bibri, 2015a), data management and analysis, database integration across urban domains, privacy and security, data growth and sharing, data uncertainty and incompleteness, data quality, urban intelligence functions, urban simulation models (e.g. Al Nuaimi et al., 2015; Batty et al., 2012; Bertot & Choi, 2013; Demchenko, Grosso, De Laat, & Membrey, 2013; DeRen et al., 2015; Fan & Bifet, 2013; Khan et al., 2014a,b; Kitchin 2014; Krogstie & Gao, 2015; Malik, 2013; Mann, 2012; Solanas et al., 2014; Townsend, 2013), and modeling and management of contextual information in large-scale distributed pervasive applications and in open and dynamic pervasive environments (e.g. Bibri, 2015a; Strimpakou, Roussak, Pils, & Anagnostou, 2006). Adding to these technical challenges are the financial, organizational, institutional, and regulatory ones, which are associated with the use, implementation, retention, and dissemination of big data. Controversies over the application and benefit of big data analytics relate to representativeness, limited access and related divide, and ethical concerns about accessibility (Fan & Bifet, 2013). Nevertheless, by advancing the existing knowledge on the available processing, analysis, and management capabilities associated with big data analytics and context–aware computing in terms of conceptions, tools, principles, paradigms, methodologies, and risks, the goal of making cities smartly more sustainable as to their systems and domains and the underlying operations, functions, services, and designs will be attainable. This entails though ensuring the current open issues stemming from those challenges are under investigation and scrutiny by the constituents of the technological innovation system of ICT of the new wave of computing, namely industry consortia, entrepreneurial companies, universities, research institutes, policy networks, and governmental agencies.

7. Conclusions

In this paper we provided a comprehensive overview of the field of smart (and) sustainable cities in terms of its underlying foundations and assumptions, state–of–the art research and development, research opportunities and horizons, emerging scientific and technological trends, and future planning practices. This work entailed exploring an extensive and broad array of literature from, and at the intersection of, different disciplinary areas. Hence, it is a means to facilitate collaboration among and between the academic disciplines of urban planning and design, sustainable development, sustainability science, and ICT for the primary purpose of generating the interactional knowledge necessary for a more integrated understanding of the topic of smart sustainable cities. This is a key contribution that supports smart urban planning and development foundational ethos of interdisciplinarity.

The results of this interdisciplinary review allowed us to establish the status of current knowledge, and highlight several avenues for research, within the area of smart sustainable urban planning and development. The key relevant concepts, theories, and discourses are identified and discussed, and their definitions are provided and elaborated on, while highlighting important issues relating to the cross–disciplinary integration underlying the topic of smart sustainable cities. The findings show that existing smart city approaches and models of sustainable urban form are associated with many issues and challenges—when it comes to their development and implementation as to the incorporation of and contribution to the fundamental goals of sustainable development, respectively. The issues revolve around shortcomings, difficulties, uncertainties, paradoxes, and fallacies in relation to existing models of sustainable urban form, in particular compact city and eco–city, and around misunderstandings, deficiencies, and discrepancies in connection with existing smart city approaches. Therefore, there are several critical questions to address or problems to investigate concerning definitional, conceptual, theoretical, analytical, evaluative, empirical, and practical aspects.These constitute research opportunities for both smart and sustainable cities, which are open for scholars and practitioners in the field to consider. The questions pertaining to our study are specifically of an applied theoretical nature, and involve how sustainable urban forms can be better monitored, understood, analyzed, assessed, and planned with support of ICT of the new wave of computing to advance their contribution to sustainability. This is anchored in the underlying assumption that emerging and future ICT as a set of enabling and constitutive technologies (and their novel applications, data analytics capabilities, and services) can make substantial contributions in this regard—not only in terms of catalyzing and boosting the sustainable development processes of sustainable urban forms, but also in terms of planning these forms in terms of their functioning, management, and development in ways that continuously evaluate and forecast their contribution to sustainability and thus strategically advance it. Currently, one of the current formidable challenges lies in the development of a robust model of smart sustainable urban form with specified and clear typological, architectural, infrastructural, operational, and functional components and their integration with advanced ICT solutions and approaches. Hence, our overall perspective on the topic is to produce a theoretically and practically convincing model of smart sustainable urban form—with a high replicative capacity—or a framework for strategic smart sustainable urban development. This is one of the many research opportunities currently available, as corroborated in this paper, that can be realized in the realm of smart sustainable cities.

We conclude that the applied theoretical inquiry into smart sustainable cities of the future is deemed of high pertinence and importance—given that the research in the field is still in its early stages, and that the subject matter draws upon contemporary and influential theories with practical applications. This entails investigating the application of a set of integrated theories, namely urban planning and design, sustainable development, sustainability science, and ICT, as a foundation for future urban practices. Specifically, the focus is on exploring the potential for ICT of the new wave of computing to provide the technological infrastructures, solutions, and approaches needed for advancing the contribution of sustainable urban forms to the goals of sustainable development based on sustainability science. This involves developing a novel model of smart sustainable city—grounded in an effective integration of emerging and future ICT with the typologies and design concepts of existing sustainable urban forms. The underlying assumption is that ICT of the new wave of computing will result in a blend of advanced solutions and methods enabled by constellations of instruments across many spatial scales linked via multiple networks for providing continuous data coming from various urban domains, which can provide a fertile environment for smartening up the way urban sustainability can be improved. The rationale is that the contribution of existing models of sustainable urban form to sustainability has, over the last two decades or so, been subject to much debate, generating a growing level of criticism that essentially questions its practicality, intellectual foundation, and added value. As we have been at pains to point out throughout this paper, the focus is on smart sustainable urban planning and development, an approach that is driven by the quest for addressing several unsolved and unexplored issues surrounding existing sustainable urban forms as to their contribution to sustainability and its evaluation, prediction, and enhancement with support of innovative solutions and sophisticated approaches enabled by emerging and future ICT.

A research plan framing the valid research aims, objectives, questions, and methodologies for the entire research endeavor will follow. But as yet our quest is to provide information relating to the background and context of our study, highlight where excess research exists, state the key problems in terms of where new research is needed, and show how the relevant gaps can be filled in the existing knowledge within the field. To elucidate more as to the gaps in question, the need for the applied theoretical inquiry in the field of smart sustainable cities, coupled with the difficulty surrounding both the evaluation of the contribution of sustainable urban forms to sustainability as well as the translation of sustainability into the built and infrastructural components of these forms provides a strong motivation for our research pursuit. Addressing these research issues is deemed of significance and timeliness. In addition, it is academically worthy to engage in a scholarly endeavor that lies at the interface of topical subjects, i.e. of immediate relevance due to their relation to current urban phenomena.

As to the value of this literature review, the findings enable researchers to focus their work on the identified real–world challenges pertaining to and the existing gaps between smart and sustainable cities as urban development strategies, and thus to contribute to the improvement of urban sustainability with support of smart ICT. Practitioners can use these findings to identify common weaknesses and potential solutions in smart sustainable urban planning and development initiatives and projects.

Lastly, we consider that this paper provides a form of grounding for further discussion to debate over the point that emerging and future ICT has disruptive, substantive, and synergetic implications, particularly on forms of urban functioning, planning, and development that are necessary for urban sustainability practices in the future. This paper also presents a basis for encouraging in–depth research on smart sustainable cities, especially applied theoretical investigations, thorough qualitative analyses, and empirical studies focused on establishing, uncovering, and substantiating the assumptions underlying the substance behind the smart strand of sustainable urban planning and development initiatives in an increasingly technologized and computerized urban society.

Competing interests

The authors declare that they have no financial and non–financial competing interests.

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Authors' contributions

SEB and JK made equally substantive intellectual contributions to the study. They have made substantial contributions to the collection and analysis of data, have been involved in drafting the manuscript and revising it critically for important intellectual content; and have given the final approval of the current version to be published.

Submitting author's information

SEB is a Ph.D scholar in the area of smart sustainable cities of the future and a teaching assistant at the Norwegian University of Science and Technology (NTNU), Department of Computer and Information Science and Department of Urban Design and Planning, Trondheim, Norway. His true passion for academic and lifelong learning and a natural thirst for interdisciplinary knowledge has led him to wittingly and voluntarily pursue an unusual academic journey by embarking on studying a diverse range of academic subject areas—at the intersection of computer science and the social sciences. His intellectual pursuits and endeavors have resulted, hitherto, in an educational background encompassing knowledge from, and meta–knowledge about, different academic disciplines. He holds a Bachelor of Science in computer engineering with a major in ICT strategy, research–based Master of Science in computer science with a major in ICT for sustainability, Master of Science in computer science with a major in informatics, Master of Science in entrepreneurship and innovation with a major in new venture creation, Master of Science in strategic leadership toward sustainability, Master of Science in sustainable urban planning, Master of Social Science with a major in business administration (MBA), Master of Arts in communication and media for social change, Master of Science in computer and systems sciences with a major in decision support and risk analysis, and postgraduate degree in management and economics. He has earned all his Master's degrees from different universities in Sweden, namely Lund University, West University, Blekinge Institute of Technology, Malmö University, and Stockholm University.

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SEB's current areas of research work include smart sustainable cities, Ambient Intelligence (AmI), Ubiquitous Computing (UbiComp), Sentient Computing (SenComp), the Internet of Things (IoT), as well as how these ICT visions of pervasive computing relate to urban design and planning, urban sustainability, efficiency of urban operations and services, and the quality of life of citizens, in addition to their core enabling technologies, namely sensor technologies, data processing platforms, cloud computing infrastructures, middleware architectures, and wireless communication networks.

SEB has a genuine interest in interdisciplinary and transdisciplinary research. In light of his varied academic background, his research interests include pervasive computing paradigms or ICT visions (i.e. AmI, UbiComp, SenComp, and the IoT), urban computing, urban informatics, big data analytics, context–aware computing, urban sustainability, sustainable city models (eco–city, compact city, green city, new urbanism, etc.), smart city approaches (knowledge city, energy–efficient city, ambient city, ubiquitous city, sentient city, real–time city, etc.), sustainability transitions and eco–innovations, green and social innovation of technology, philosophy and sociology of scientific knowledge, social construction and shaping of science–based technology, governance of sociotechnical changes in technological innovation systems, energy efficiency technology, sustainable business model innovation, and technology and innovation policy.

SEB is the author of the following recent books in the field of pervasive computing:

(1) The Human Face of Ambient Intelligence: Cognitive, Emotional, Affective, Behavioral and Conversational Aspects, Springer, 07/2015, 523 pages.
(2) The Shaping of Ambient Intelligence and the Internet of Things: Historico–epistemic, Socio–cultural, Politico–institutional and Eco–environmental Dimensions, Springer, 11/2015, 301 pages.

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Paper 2

On the Sustainability of Smart and Smarter Cities and Related Big Data Applications: An Interdisciplinary and Transdisciplinary Review and Synthesis

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SURVEY PAPER

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On the sustainability of smart and smarter cities in the era of big data: an interdisciplinary and transdisciplinary literature review

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Abstract

There has recently been a conscious push for cities across the globe to be smart and even smarter and thus more sustainable by developing and implementing big data technologies and their applications across various urban domains in the hopes of reaching the required level of sustainability and improving the living standard of citizens. Having gained momentum and traction as a promising response to the needed transition towards sustainability and to the challenges of urbanisation, smart and smarter cities as approaches to data-driven urbanism are increasingly adopting the advanced forms of ICT to improve their performance in line with the goals of sustainable development and the requirements of urban growth. One of such forms that has tremendous potential to enhance urban operations, functions, services, designs, strategies, and policies in this direction is big data analytics and its application. This is due to the kind of well-informed decision-making and enhanced insights enabled by big data computing in the form of applied intelligence. However, topical studies on big data technologies and their applications in the context of smart and smarter cities tend to deal largely with economic growth and the quality of life in terms of service efficiency and betterment while overlooking and barely exploring the untapped potential of such applications for advancing sustainability. In fact, smart and smarter cities raise several issues and involve significant challenges when it comes to their development and implementation in the context of sustainability. With that in regard, this paper provides a comprehensive, state-of-the-art review and synthesis of the field of smart and smarter cities in relation to sustainability and related big data analytics and its application in terms of the underlying foundations and assumptions, research issues and debates, opportunities and benefits, technological developments, emerging trends, future practices, and challenges and open issues. This study shows that smart and smarter cities are associated with misunderstanding and deficiencies as regards their incorporation of, and contribution to, sustainability. Nevertheless, as also revealed by this study, tremendous opportunities are available for utilising big data analytics and its application in smart cities of the future to improve their contribution to the goals of sustainable development by optimising and enhancing urban operations, functions, services, designs, strategies, and policies, as well as by finding answers to challenging analytical questions and thereby advancing knowledge forms. However, just as there are immense opportunities ahead to embrace and exploit, there are enormous challenges and open issues ahead to address and overcome in order to achieve a successful implementation of big data technology and its novel applications in such cities.

Keywords: Smart cities, Smarter cities, ICT of pervasive computing, Big data analytics, Big data applications, Urban intelligence functions, Sustainability, Sustainable development, Urban systems and domains

Introduction

Cities have a central and defining role in strategic sustainable development; and therefore, they have increasingly gained a central position in operationalising and applying it. This is clearly reflected in the Sustainable Development Goals (SGDs) of the United Nations' 2030 Agenda for Sustainable Development, which entails, among other things, making cities more sustainable and resilient [127], as well as well documented by European Commission [48]. This is anchored in the recognition that cities as the engines of, and the hubs of innovation that drive, economic development are the world's major consumers of energy resources and significant contributors to GHG emissions. It is estimated that they consume about 67% of the global energy demand and generate up to 70% of the harmful GHG emissions. Accordingly, they represent the key generators of environmental pollutants and the main hotspots of vulnerability to climatic hazards and related upheavals, in addition to social inequality, disparity, vulnerability, and insecurity [20]. In view of that, they are seen as the most important arena for instigating major sustainability transitions, adding to being the key sites of economic, environmental, and social dynamism and innovation and thereby holding great potential for making significant contributions to social transformation and thus sustainable development [22]. As such, they provide ideal testing grounds and operating environments for innovative ICT solutions pertaining to diverse urban systems and domains. In this regard, the UN's 2030 Agenda regards ICT as a means to promote socio-economic development and protect the environment, increase resource efficiency, achieve human progress and knowledge in societies, upgrade legacy infrastructure, and retrofit industries based on sustainable design principles [127, 129]. Hence, the multifaceted potential of the smart city approach as enabled by ICT has been under investigation by the UN [128] through their study on 'Big Data and the 2030 Agenda for Sustainable Development'.

Unprecedented in their magnitude and influence in history, the spread of urbanisation and the rise of ICT are among the most important global shifts at play across the world today, and will undoubtedly change urbanism in a drastic and irreversible way. As widely estimated, the urban world will become largely technologized, computerised, and urbanised within just a few decades, and ICT as an enabling, integrative, and constitutive technology of the twenty-first century will accordingly be instrumental, if not determining, in addressing many of the conundrums posed, the issues raised, and the challenges presented by urbanisation [20]. It is therefore of strategic value to start directing the use of emerging ICT into understanding and proactively mitigating the potential effects of urbanisation, with the primary aim of tackling the many intractable and wicked problems involved in urban operational functioning, management, planning, and development, especially in the context of sustainability which is another macro-shift at play across the world today. Indeed, the rapid and anticipated urbanisation of the world pose significant and unprecedented challenges associated with sustainability (e.g., [39, 46, 53]) due to the issues engendered by urban growth in terms of resource depletion, environmental degradation, intensive energy usage, air and water pollution, toxic waste disposal, endemic traffic congestion, ineffective decision-making processes, inefficient planning systems, mismanagement of urban infrastructures and facilities, poor housing and working conditions, public health and safety decrease, social vulnerability and inequality, and so on [20]. These accordingly affect the quality of life and well-being of citizens as well as the efficiency of urban operations and functions [40]. In short, the multidimensional effects of unsustainability in modern and future cities are most likely to exacerbate with urbanisation [20]. Urban growth will jeopardise the sustainability of cities [102]. Therefore, ICT has come to the fore and become of crucial importance for containing the effects of urbanisation and facing the challenges of sustainability. ICT becoming part of mainstream debate in this regard emanates from the increasing ubiquity presence of, and new discoveries in, computing, coupled with the massive use of its technological applications across various urban systems and domains. In fact, advanced sophisticated technologies and novel complex approaches are now more needed than ever to address and overcome the challenges and issues facing modern and future cities. This pertains to the way these cities should be monitored, understood, analysed, and, hence, operated, managed, organised, and planned to improve and maintain their contribution to the goals of sustainable development. There is an increasing recognition that emerging and future ICT constitutes a promising response to the challenges of urban sustainability due to its tremendous, yet untapped, potential to catalyse and boost sustainable development processes (e.g., [6, 16, 20, 24, 25, 82]. Many urban development approaches reference the role of ICT in achieving the goals of sustainable development (e.g., [4, 6, 20, 122]. As pointed out by Bibri [20], ICT constitutes an effective approach to decoupling the health of the city and the quality of life of citizens from the energy and material consumption and concomitant environmental risks associated with urban operations, functions, services, designs, and policies.

In the wake of the rapid advancement of ICT of various forms of pervasive computing, recent research has started to focus on incorporating sustainability in the smart city concept and approach (e.g., [5, 6, 102]). The underlying assumption is that, as ICT becomes spatially omnipresent across urban environments, i.e., data sensing, data processing, cloud/fog computing, and wireless communication networking become more and more combined with infrastructure, architecture, ecosystem services, human services, and even citizens' bodies, smart cities can become smarter and also so as to solving environmental problems and responding to socio-economic needs (e.g., [16, 20, 106, 113, 124]). Therefore, most of the prospects and opportunities in this regard relate to what is labeled 'smarter cities', a class of cities which is viewed as future visions of smart cities, and is characterised by an ever-growing embeddedness and pervasion of ICT into the very fabric of the city [20]. They include ubiquitous cities, sentient cities, ambient cities, real-time cities, and cities as Internet-of-everything. For these cities, big data analytics is seen as a critical enabler and powerful driver in regard to the transformation of their ecosystem on several scales, including the way sustainability can be understood, applied, and planned.

Undoubtedly, the main strength of the big data technology is the high influence it will have on smart cities of the future or smarter cities and on citizens' lives (e.g., [5, 16, 18, 20, 54, 73, 79, 83, 104, 124]). Thereby, the notion of big data analytics and its application in sustainable urban development has gained traction and foothold among urban scholars, scientists, practitioners, and policymakers over the past few years. Indeed, big data computing as a new paradigm is fundamentally changing the way modern cities can sustainably be operated, managed, planned, and developed, shaping and driving decision-making processes within many urban domains [20], especially with regard to optimising resource utilisation, mitigating environmental risks, responding to socio-economic needs, and enhancing the quality of life and well-being of citizens in an increasingly urbanised world. This paradigm is clearly on a penetrative path across all the systems and domains of smart and smarter cities that rely on advanced ICT in relation to operational functioning, management, planning, and development. This is manifested in the proliferation and increasing utilisation of the core enabling technologies of big data analytics across those cities badging or regenerating themselves as both smart and smarter for storing, managing, processing, analysing, and sharing colossal amounts of urban data for the primary purpose of extracting useful knowledge in the form of applied intelligence functions and simulation models. Big data are regarded as the most scalable and synergic asset and resource for smart and smarter cities to enhance their performance on many scales, as they have become the fundamental ingredient for the next wave of urban analytics [20]. As a result, many governments have started to exploit urban data and their numerous benefits to support the development of smart and smarter cities across the globe with regard to sustainability, efficiency, resilience, equity, and the quality of life. However, to facilitate big data analytics and achieve a successful implementation of the associated applications and services towards reaching this goal, huge investments in the underlying core enabling technologies are needed.

However, according to a recent literature review [25], while smart and smarter cities have played a key role in transforming different areas of human life, they are still associated with misunderstanding and deficiencies with regard to incorporating the goals of sustainable development. Also, there is a weak connection between smart targets and sustainability goals [6, 20, 28], despite the proven role of ICT in supporting modern cities in moving towards sustainability [25]. On this note [6], conclude that the smart city and sustainable city landscapes are extremely fragmented both on the policy and the technical levels, and there is a host of unexplored opportunities toward sustainable smart city development. In all, smart and smarter city approaches raise many issues and present significant challenges in the context of sustainability (e.g., [2, 20]).

Concerning big data analytics and its application, while research has recently been active in the realm of smart and smarter cities, the bulk of work tends to deal largely with economic growth (management, efficiency, innovation, productivity, etc.) and the quality of life in terms service efficiency and betterment (e.g., [15, 54, 73, 79, 83, 108]), while overlooking and barely exploring the untapped potential of big data applications for advancing the different aspects of sustainability. Indeed, many of the emerging smart solutions are not aligned with sustainability gaols [2]. In view of that, smart and smarter cities need to direct their focus towards utilising big data applications for improving their contribution to the goals of sustainable development across urban domains [20].

This paper provides a comprehensive, state-of-the-art review and synthesis of the field of smart and smarter cities as regards sustainability and related big data analytics and its application in terms of the underlying foundations and assumptions, research issues and debates, opportunities and benefits, technological developments, emerging trends, future practices, and challenges and open issues. This extensive interdisciplinary and transdisciplinary review and synthesis endeavours to present a detailed analysis and synthesis and critical evaluation and discussion of the available qualitative and quantitative research covering the topic of smart and smarter cities, with a particular emphasis on cross- and beyond disciplinary forms of knowledge. It is deemed important to identify and stimulate new research opportunities in the field. The added values of this review involve thoroughness, comprehensiveness, topicality, and original contribution in the form of novel insights as a result of analysing, synthesising, and critically evaluating a large body of recent works. The main motivation for this paper is to capture further and invigorate the application demand for the urban sustainability solutions that big data analytics can offer in the context of smart and smarter cities.

The remainder of this paper is structured as follows. "Methodical-topical literature review methodology" section outlines the literature review and synthesis methodology in terms of approach, search, selection, organisation, and purpose. In "Conceptual, theoretical, and discursive foundations and assumptions" section, the relevant conceptual, theoretical, and discursive foundations and assumptions are presented, described, and discussed. "A detailed survey of relevant work: issues, debates, gaps, benefits, challenges, opportunities, and prospects" section provides a detailed, two-part survey of the relevant work in terms of issues, debates, gaps, benefits, opportunities, and prospects. The first part addresses smart cities in terms of general and particular research strands, deficiencies, and potentials with regard to sustainability, as well as smarter cities in terms of characteristic features, social shaping dimensions, and the current issues of and future potentials for sustainability. The second part covers big data analytics and its application in smart and smarter cities in terms of research status and data growth projection, the urban data deluge in city analytics and its sources and enabling capabilities, research issues and future prospects, core enabling technologies, and big data applications and their sustainability effects and benefits (specifically covering a critical evaluation of topical studies, analytical and practical applications for multiple smart/smarter city domains, and data-driven sustainable smart cities). "The main scientific and intellectual challenges and common open issues" section identifies the key scientific and intellectual challenges and sheds light on the common open issues associated with the use of big data analytics and related applications in (enabling, operating, managing, and planning) smart and smarter cities. The paper ends, in "Discussion, conclusion, and contribution" section, with concluding remarks, findings, reflections, and contributions.

Methodical-topical literature review methodology

This extensive review and synthesis involves the exploration of a vast and diverse array of literature on the topic (including journal articles, conference proceedings, books, reports, and dissertations), and integrates and fuses various disciplinary, scientific, and technological areas at the core of this study, with an emphasis on the qualitative research in the field. In light of this, and given moreover the nature of this topic, adopting a topical approach to this review and synthesis is deemed more relevant than a systematic one. Indeed, this paper determines the usefulness of this substantive category of review and synthesis to this endeavour. In addition, this review and synthesis is methodical in the sense that it is arranged according to, characterised by, or performed with a method or order. Also, it is done based on a loose coupling of technical and social perspectives (e.g., [87, 140]). In view of that, a review and synthesis method is developed as a means to indicate the issues (concepts, theories, academic discourses, themes, and topics) to be addressed, search strategy for retrieving the sought articles and other documents, inclusion and exclusion criteria for identifying and selecting the relevant ones, and abstract review protocols. Prior to delving into such method, it is useful to elucidate what the interdisciplinary and transdisciplinary approach entails in the context of this paper.

Interdisciplinary and transdisciplinary approach

Interdisciplinarity and transdisciplinarity have become a widespread mantra for research within diverse fields, accompanied by a growing body of academic publications. The field of sustainable smart and smarter cities is profoundly interdisciplinary and transdisciplinary in nature, so too is research within, and thus literature on, it. This also applies to any review and synthesis of this literature, which is accordingly multidisciplinary as well in the sense of using insights and methods from several disciplines, or involving several disciplines in an approach to a problem or topic. These disciplines include, but are not limited to: urban planning, urban development, geography, sustainable development, sustainability science, environmental science, data science, computer science, ICT, systems thinking, complexity science, policy, and innovation. However, multidisciplinary efforts remain limited in impact on theory building for coping with the changing human condition [99]. Clearly, sustainable smart and smarter city research naturally lends itself to multidisciplinary, interdisciplinary, and transdisciplinary approaches and strategies (e.g., [20, 138]). For a descriptive account of the interdisciplinary and transdisciplinary approaches to research, the interested reader can be directed to Bibri [20, 22]. However, they all require conceptual precision in order for research outcomes to be valid and usable (e.g., [89]). In all, this interdisciplinary and transdisciplinary literature review and synthesis is a topical, analytical, and organisational unit that is justified and determined by the essence and orientation of the research field of sustainable smart and smarter cities in terms of the underlying scholarly approach. As such, it is an opportunity to situate the researcher in an ecology of ideas, a process which can be approached from the perspective of complexity and intricacy. In this respect, the key dimensions that can be considered, especially in relation to transdisciplinarity, include: integrating rather than eliminating the researcher from the research, meta-paradigmatic rather than intra-paradigmatic, research-grounded rather than discipline-grounded, and applying systems and complexity thinking rather than reductionism.

Hierarchical search strategy and scholarly sources

A literature search is the process of querying quality scholarly literature databases to gather applicable research documents related to the topic under review. A broad search strategy was used, covering several electronic search databases, including Cristin, NTNU Open, Scopus, ScienceDirect, SpringerLink, ACM digital library, and Sage Journals, in addition to Google Scholar. The main contributions came from the leading journal articles in relevance to the topic on focus. The hierarchical search approach to searching for literature involved the following:

- Searching databases of reviewed high quality literature;
- Searching evidence based journals for review articles; and,
- Routine searches and other search engines.

In addition, the collection process is based on [111] four criteria for assessing the quality of the sought material, namely:

1. Authenticity: the evidence gathered is genuine and of unquestionable origin.
2. Credibility: the evidence gathered is free from error and distortion.
3. Representation: the evidence obtained is typical.
4. Meaning: the evidence gathered is clear and comprehensible.

Selection criteria: inclusion and exclusion

To find out what has already been written on the topic of this multifaceted study, the above search approach was adopted, whose objective was to identify the relevant studies addressing the diverse research strands that constitute this interdisciplinary and transdisciplinary review and synthesis. The preliminary selection of available material was done in line with the issues being investigated as pertaining to those strands, using a variety of sources that are up-to-date and authoritative.

The selection was initially bounded with the issues intended to be investigated in relation to the topic of this study. This is underpinned by the recognition that once the research issues are set, it becomes possible to refine and narrow down the scope of reading, although there may seem to be hundreds of sources of information that appear pertinent [25]. With that in mind, for an article or document to be considered of relevance for providing information or evidence on the issues in question, it should cover one of the conceptual/theoretical subjects or thematic/topical categories intended to be examined, as demonstrated by the sections and subsections of this paper. The focus was on the articles and documents that provided definitive primary information or evidence from an interdisciplinary and/or transdisciplinary perspective. While certain methodological guidelines were deemed essential to ensure the validity of the review, it was of equal importance to allow flexibility in the application of the topical literature review and synthesis methodology to capture the essence of research within the interdisciplinary and transdisciplinary field on focus. The whole idea was to 'accumulate a relatively complete census of relevant literature' [140]. In all, scoring the articles and documents was based on the inclusion of issues relating to the topic on focus. Conversely, the articles and documents excluded were those that did not meet specific criteria in terms of their relevance to the issues being addressed. As to abstract review, the abstracts were reviewed to assess their pertinence to the review and to ensure a reliable application of the inclusion and exclusion criteria. Inclusionary discrepancies were resolved by the re-review of abstracts. The process allowed to further refine and narrow down the scope of reading.

The keywords searched included 'smart cities', 'smart cities AND sustainability', 'smart cities AND big data analytics', 'smart cities AND big data applications', 'smart cities AND sustainability AND big data applications', 'smart cities AND sustainable cities', 'smarter cities AND sustainability', 'smarter cities', 'ambient cities', 'sentient cities', 'ubiquitous cities', 'real-time cities', 'data-driven cities', 'smart cities and the IoT', 'smarter cities AND big data applications', and 'smarter cities AND sustainability AND big data applications', and 'urban sustainability AND big data applications', and 'sustainable urban development and smart applications', in addition to the derivatives of these keywords. These were used to search against such categories as the articles' keywords, title, and abstract to produce some initial insights into the topic. To note, due to the potential limitations associated with relying on the keyword approach, backward literature search (backward authors, backward references, and previously used keywords) and forward literature search (forward authors and forward references) were additionally used to enhance the search approach [140].

Combining three organisational approaches

This literature review and synthesis is structured using a combination of three organisational approaches, namely thematic, inverted pyramid, and the benchmark studies. That is to say, it is divided into a number of sections representing the conceptual and theoretical subjects and the thematic and topical categories for the topic of sustainable smart and smarter cities. The examination and discussion of relevant issues is organised accordingly while, when appropriate, starting from a broad perspective and then dealing with a more and more specific one in terms of studies. In doing so, the focus is on the major writings and publications considered as significant in the field.

Purpose

The literature review is typically performed to serve many different purposes, depending on whether or not it is motivated by, or an integral part of, a research study, as well as on its focus, scope, and aim. Within the scope of this paper, however, it was carried out with the following specific objectives in mind:

- To examine and discuss the underlying foundational constructs and their integration and fusion from an interdisciplinary and transdisciplinary perspective, respectively.
- To analyse, evaluate, and synthesise the existing knowledge in line with such constructs as set for this study.
- To highlight the strengths, weaknesses, omissions, and contradictions of the existing knowledge, thereby providing a critique of the research that has been done within the field and related subfields.
- To discuss the identified strengths and weaknesses, with an emphasis on the performance of smart and smarter cities with respect to sustainability and the untapped potential of big data applications for its advancement in the future.
- To identify and discuss the knowledge gaps and opportunities within the field with regard to sustainability and related big data applications.

- To identify the key relationships between the research findings by comparing various studies addressing the different topics of the study, with a particular focus on sustainability and related big data applications.

Conceptual, theoretical, and discursive foundations and assumptions

Smart cities

According to a recent review conducted by Bibri and Krogstie [25], the roots of the smart city concept date back to the 1970s under what is labeled the 'cybernetically planned cities', and then in urban development and planning proposals associated with networked or wired cities since the 1980s. Several views claim that the concept was introduced in 1994 [38], and that it is only until 2010 that the number of publications and scientific writings on the topic increased considerably, after the emergence of smart city projects as supported by the European Union [65]. As echoed by Neirotti et al. [102], the smart city concept's origin can be traced back to the smart growth movement during 1990s. Yet, it is not until recently that this movement led this concept to be adopted within urban planning and development [16]. However, regarding its early conceptualisation and connotation, the concept was mostly associated with the efficiency of technological smart solutions with respect to the operational functioning, management, and planning pertaining to energy, transport, physical infrastructure, distribution and communication networks, economic development, service delivery, and so forth. Smart growth implies the ability of achieving greater efficiencies through coordinating the forces that lead to free growth (do-nothing policy): transportation, land use speculation, resource conservation, and economic development, rather than letting the market dictate the way cities grow [16]. At present, however, many cities across the globe compete to be smart cities in the hopes of reaping the efficiency benefits economically, socially, or, more recently, environmentally by taking advantage from the opportunities made possible by big data analytics and its wider application across urban domains. It is also in this context that it has increasingly become attainable to achieve the required level of sustainability, resilience, and equity, in addition to improving the quality of life and ensuring higher levels of transparency and openness and hence democratic and participatory governance, citizenry participation, and social inclusion. Achieving all these benefits require sophisticated approaches, advanced technologies and their novel applications and services, resources, financial capabilities, regulatory policies, and strategic institutional frameworks, as well as an active involvement of citizens, institutions, and organisations as city constituents. Worth noting is that the growing interest in building smart cities based on big data analytics as an advanced technology is increasingly driven by the needs for addressing the challenges of sustainability and to contain the effects of urbanisation. Besides, the main features of smart cities have become a high degree of information and technology integration and a comprehensive application of computing resources.

In recent years, the smart city as a catchphrase and phenomenon has drawn increased attention and gained traction among universities, research institutes, governments, policymakers, businesses, industries, and consultancies across the globe. Notwithstanding this prevalence worldwide, the smart city concept is still without a universally agreed definition. In other words, a shared definition of smart city is not yet available or offered. It is difficult to identify common trends of smart cities at global level [102]. Moreover, despite the wide use of the concept and its operationalisation today, there is still obscure and inconsistent understanding of its meaning (e.g., [2, 5, 8, 16, 20, 25, 36, 93, 119, 137]). Consequently, multiple meanings have been, and continue to be, adopted by different people within different contexts. The concept having different connotations and being approached from a variety of perspectives is clearly manifested in the various ways in which many governments set initiatives or implement projects to enable their cities to become, badge, or regenerate themselves as, or manifestly plan to be, smart. In all, a large number and variety of definitions (e.g., [3, 5]) have been suggested with different foci and orientations. Table 1 depicts a set of other definitions of smart cities with other foci and orientations.

The smart city continues to be a difficult concept to pin down or strictly delineate. The best way of looking at it is by the context within which it can be applied, as hinted at above. This implies that smart city projects, programs, and initiatives tend to be based on specific objectives, technological capabilities, financial abilities, human and social resources, regulatory policies, institutional frameworks, political mechanisms, governance arrangements, and so on [20]. They can also be determined or driven by the state-of-the-art research, development, and innovation in the area of ICT and related applications, infrastructures, platforms, systems, models, methods, computational analytics, and so forth. However, in relation to the objectives, for example, Batty et al. [16] identify a number of smart city projects, including modelling urban land use; modelling network performance; sensing, networking, and the impact of social media; mobility and travel behaviour; transport and economic interactions; integrated databases across urban domains; participatory governance and planning structures; and decision support as urban intelligence. Concerning the financial abilities, many governments are funnelling huge expenditures (colossal investments) into ICT research, development, and innovation, which is manifested in the high number of jointly funded research endeavours as well as smart initiatives and implementation projects (e.g., [2]).

Table 1 Definitions of smart cities

Different foci and orientations of smart city definitions
'A smart city is…a city which invests in ICT enhanced governance and participatory processes to define appropriate public service and transportation investments that can ensure sustainable socio-economic development, enhanced quality-of-life, and intelligent management of natural resources' [5]
'A smart city is a very broad concept, which includes not only physical infrastructure but also human and social factor' [102]
'Connecting the physical infrastructure, the IT infrastructure, the social infrastructure, and the business infrastructure to leverage the collective intelligence of the city… A city striving to make itself "smarter" (more efficient, sustainable, equitable, and livable' [36]
'Smart cities is a term…that describe cities that, on the one hand, are increasingly composed of and monitored by pervasive and ubiquitous computing and, on the other, whose economy and governance is being driven by innovation, creativity and entrepreneurship, enacted by smart people' [79, p. 1]
A smart city is 'a city in which ICT is merged with traditional infrastructures, coordinated and integrated using new digital technologies' [16]
'As presently understood, a smart city is one that strategically uses networked infrastructure and associated big data and data analytics to produce a: *smart economy…*; *smart government…*; *smart mobility…*; *smart environments…*; *smart living…*; and *smart people…*' [80, p. 8]

Yet, scholars, academics, planners, ICT experts, and policymakers converge on the idea that the use of ICT pertains to all domains of smart cities, and hence on considering it as an inseparable facet thereof [20]. In this line of thinking, a common thread running in most of the definitions of smart city is its characteristic features and technological components, which are usually observed in smart city proposals, projects, and initiatives, irrespective of their scale, scope, national context, and available resources. In the context of this paper, however, a smart city can be described as a city that is increasingly composed of, and monitored and operated by, various forms of pervasive computing, as well as whose planning and governance are being driven by innovation as enacted by various stakeholders that capitalise on and exploit cutting-edge technologies in their endeavours and practices. In this light, being instrumented and pervaded with digital devices, systems, and platforms that generate big data, smart cities can enable real-time analysis of urban life, environment, and dynamics as well as new modes of urban planning and governance, and also provide the conditions that are conducive to envisioning and enacting more sustainable, efficient, resilient, transparent, and open human and urban environments. Accordingly, a smart city can also be taken to mean a technologically and data-analytically advanced city that is able to understand its environment and citizens and explore and analyse various forms of urban data to generate useful knowledge in the form of applied intelligence that can immediately be used to solve different kinds of problems, or to make changes to improve the quality of life and the health of the city in terms of sustainability, efficiency, and resilience. In this line of conceptualisation, Batty et al. [16] describe smart cities as 'constellations of instruments across many scales that are connected through multiple networks which provide continuous data regarding the movements of people and materials in terms of the flow of decisions about the physical and social form of the city'. However, the financial abilities, human/social resources, and regulatory policies required to develop, implement, and sustain smart cities are the most significant challenges governments around the world are concerned about and are dealing with. Positively, the emerging technologies such as big data analytics hold great potential to transform such challenges into opportunities.

Furthermore, based on a recent survey of the field of smart cities [25], there are two main approaches to smart city: (1) the technology-oriented approach, i.e., infrastructures, architectures, platforms, systems, applications, and models and (2) the people-oriented approach, i.e., stakeholders, citizens, knowledge, services, and related data [20]. In other words, there are smart city strategies that focus on the efficiency and advancement of hard infrastructures in terms of transport, energy, communication, and distribution networks, and so on (e.g., [45, 52, 74, 79, 83, 93]) and those that prioritise the soft infrastructures in terms of social and human capital, participation, equity, safety, cultural heritage, and so forth (e.g., [7, 17, 75, 76, 88, 102]). There are also smart city strategies that combine these two perspectives (e.g., [16, 73]). To gain a broad understanding of the concept of smart city, the interested reader can be directed to Song et al. [119] who provide a detailed overview of the foundations, principles, and applications of smart cities. Also, Nam and Pardo [101] conceptualise smart city with the dimensions of technology, people, and institutions.

It is of particular relevance in this paper to highlight the body of the literature focusing on the defining role of ICT (e.g., big data analytics and its application) as well as human and social capital in smart cities in terms of the dimensions of sustainability (e.g., [5, 6, 10, 16, 82, 102]). This strand of research is concerned with smart cities as urban innovations whose focus is on advancing, harnessing, and integrating physical, human, and social infrastructures for environmental protection, economic regeneration, and enhanced public and social services [20]. The most cited definition in this regard is provided by Caragliu et al. [30]: a city is smart city 'when investments in human and social capital and traditional (transport) and modern (ICT) communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory governance.' This definition is linked to a model that has been used as a ranking system—developed based on six smart dimensions, namely, economy, environment, mobility, living, people, and governance—against which smart cities can be assessed in terms of their development and implementation. However, this model neither specifies how these dimensions can be prioritised as to the contribution to sustainability, nor how they can, combined, add value to sustainable development. However, as an extension of this definition, Pérez-Martínez et al. (2013, cited in [2]) describe smart cities as 'cities strongly founded on ICT that invest in human and social capital to improve the quality of life of their citizens by fostering economic growth, participatory governance, wise management of resources, sustainability, and efficient mobility, whilst they guarantee the privacy and security of the citizens.' In this line of thinking, Batty et al. [16, pp. 481–482] describe smart cities as cities 'in which ICT is merged with traditional infrastructures, coordinated and integrated using new digital technologies,' and where 'intelligence functions…are able to integrate and synthesise…[urban] data to some purpose, ways of improving the efficiency, equity, sustainability, and quality of life in cities.' In all, this view of smart cities highlights—at the level of discourse though—the potential of ICT in catalysing and improving sustainable development processes. In this context, a sustainable smart city is an innovative city that uses ICT and other means to improve the efficiency of urban operations, functions, and services as well as enhance the quality of life of citizens, 'while ensuring that it meets the needs of present and future generations with respect to economic, social, environmental as well as cultural aspects' [130].

In light of the above analytical account, the available definitions of smart cities have several commonalities as well as distinctions, i.e., converging on some dimensions and diverging on others apart from technological aspects, including economic, environmental, physical, political, social, cultural, institutional, organisational, and futuristic, in addition to the extent of different sustainability dimensions and their integration. Yet, the majority of these definitions tend to focus on integrated solutions for achieving a sustainable utilisation of resources, efficient operation of infrastructures and facilities, high quality of life, and effective urban planning and governance. In more detail, as an attempt to provide a comprehensive definition of smart city from a generic perspective that combines the core features of smart cities as a broad concept [20], describes smart city as a city that badges or regenerates itself as smart, or manifestly plans to be so, in terms of achieving efficiency, sustainability, resilience, equity, and livability by investing in, and hence enhancing and continuously advancing, the ICT infrastructure, physical infrastructure, economic infrastructure, and social infrastructure to leverage collective intelligence for the purpose of integrating urban systems and coordinating urban domains in ways that these components exceed their sum as to the collective behaviour of the whole city. In other words, it is an innovative city that focuses on developing, implementing, and applying advanced ICT to all its systems and domains, and accordingly perform in an innovative, forward-looking, strategic, and participatory way to enhance its key features: environment, economy, people, mobility, living, and governance, on the basis of the intelligent combination of endowments and activities of independent and aware citizens together with other urban stakeholders (organisations, institutions, industries, enterprises, etc.), thereby ensuring and maintaining socio-economic development, the quality of life, the efficiency of service delivery, the intelligent management of natural resources, and the optimised operation of infrastructures and facilities—ideally in line with the fundamental goals of sustainable development.

Smarter cities and other faces of cities

Smart cities come in many faces depending on the way ICT is applied, the extensiveness of its use, the degree and form of its ubiquity, and/or the focus of its orientation, as well as the kind of digital technology by which it is coordinated and integrated [20]. The common faces that emerged before, or in parallel with (only for a few of them), the adoption of the concept of smart city in urban planing and development around the mid 1990s include: networked cities, wired cities, cyber cities, digital cities, virtual cities, intelligent cities, knowledge cities, and cyber cities, among other nomenclatures. For example, digital cities tend to focus on the hard infrastructure whereas intelligent cities on the way such infrastructure is used [12–14], and wired cities embrace ICT as a development strategy, pioneer in embedding digital infrastructure and systems into their urban fabric and utilize them for entrepreneurial and regulatory effect [43]. However, they all share a focus on the effects of ICT on urban forms, processes, and modes of living, and have largely been subsumed within the label 'smart cities' in recent years, although each of those terms is used in a particular way to conceptualize the relationship between ICT and contemporary urbanism [79]. There are also hybrid cities which merge two faces of smart cities or one from smart/smarter cities and one from sustainable cities, such as cyber-physical cities, ubiquitous eco-city, knowledge eco-city, and smart compact city, and so forth. In addition to these faces are the ones that are inspired by the prevalent ICT visions of pervasive computing, including ambient cities, sentient cities, ubiquitous cities, real-time cities, and cities as Internet-of-everything (e.g., [79, 84, 105, 108, 113, 114, 123, 143]). For example, the real-time city is likely to become a reality in many cities over the next decade, as urban administrations seek to capitalise on new data streams and new products are bought to market that help governments and citizens make sense of the city [79]. These cities have materialised as a result of the advance of ICT of pervasive computing, or rather the evolvement of the dominant ICT visions into achievable and deployable computing paradigms. Seen as future forms of smart cities, they are quite different from what has been experienced hitherto in terms of smartness and its effects on human life at several levels. They have come to be identified or labelled as 'smarter cities' due to the magnitude of ICT and the extensiveness of data with regard to their application and use across urban systems and domains. The prospect of smarter cities is increasingly becoming the new reality with the massive proliferation of the core enabling technologies underlying ICT of pervasive computing, namely sensor networks, data processing platforms, wireless communication networks, and cloud and fog computing models across different spatial scales [25]. The initiatives of smarter cities in several countries across Europe, the USA, and Asia are considered as national urban development projects epitomising the increasing significance and role of advanced ICT, especially big data analytics, in enhancing the operations, functions, services, strategies, and policies of smart cities of the future associated with planning, management, development, and governance [20]. The conceptualisation of smarter cities is built upon the core features of the prevalent ICT visions in terms of the pervasion of technology into the very fabric of the city, the omnipresence and always-on interconnection of computing resources, applications, and services across many spatial and temporal scales. The emerging connotations of smart cities of the future or smarter cities are numerous. Townsend [124] defines a smart city as an urban environment where ICT 'is combined with infrastructure, architecture, everyday objects, and even our own bodies to address social, economic and environmental problems'. Piro et al. [106] conceive of it 'as an urban environment which, supported by pervasive ICT systems, is able to offer advanced and innovative services to citizens in order to improve the overall quality of their life'. Su et al. [121] describe it as city which mainly focuses on embedding the next-generation of ICT into every conceivable object or all walks of life, including roads, railways, bridges, tunnels, water systems, buildings, appliances, hospitals, and power grids, in every corner of the world, and constituting the IoT. In addition, the concept of smarter cities has been associated with the orientation of smart cities towards achieving the goals of sustainability in the future. In this line of thinking Chourabi et al. [36], describe a smart city as a city which strives to become smarter as to making itself more sustainable, equitable, efficient, and livable. This is also consistent with what smart cities of the future entail according to Batty et al. [16]. The underlying assumption is that smarter cities or smart cities of the future have tremendous potential compared to current smart cities as to advancing sustainability. Indeed, there has recently been a conscious push for cities in Europe to be smarter and thus more sustainable, leading to the need to benchmark these cities' efforts using advanced assessment frameworks to rank them based on how smarter and more sustainable they are. For a detailed account of smarter cities, the interested reader can be directed to Bibri [20] where there is a whole chapter about the transition of smart cites to smarter cities and the future potential of the underlying ICT of pervasive computing for advancing environmental sustainability. This is projected to happen because of the prospective advancements and innovations pertaining to big data analytics as an advanced form of ICT (e.g., [5, 16, 20]).

In light of the above, a smarter city can be understood as a city where advanced ICT is combined with physical, infrastructural, architectural, operational, functional, and ecological systems across many spatial scales, as well as with urban planning processes and governance models, with the primary aim of improving sustainability, efficiency, equity, and livability. Here, smartness should go beyond the technological advancement and efficiency of solutions to include a focused orientation towards incorporating, considering, and achieving the goals of sustainable development. Of relevance to underscore here is that current smart cities strive for smartness targets instead of sustainability goals (e.g., [2, 93]). In all, common to all smart cities of the future or smarter cities as urban development approaches is the idea that ICT is, and will be for many years yet to come, central to urban operations, functions, services, strategies, and policies.

Irrespective of which ICT vision smart cities of the future or smarter cities tend to instantiate or be built upon, whether be it Sentient Computing, Ambient Intelligence, Ubiquitous Computing, the IoT, or a combination of two or more of these technological visions, such cities are taken to mean urban spaces loaded with clouds of data intended to shape the life and experience of citizens and bring about major transformations to their environments. Here, big data analytics is given a prominent role, as all over the city, the underlying core enabling technologies can monitor urban areas (in terms of activities, citizen behaviours, events, social dynamics, locations, spatiotemporal settings, environmental states, etc.); analyse, interpret, evaluate, model, and simulate the continuously collected steams of data; and then deploy the obtained results in the form of intelligence and planning functions applicable to various urban domains across several spatial scales. While the current notion of smart cities can 'be understood as a collection of plural research traditions, performed and commissioned by divergent actors all with their own motivation and implicit understanding of what a city is or should be' [113], the impetus behind the concept of smarter cities or smart cities of the future [16, 20] based on big data analytics and its application—is to mobilise and align urban stakeholders through research and development endeavours for the purpose of promoting and advancing sustainability by using advanced ICT to continuously evaluating and strategically planning the contribution of such cities to the goals of sustainable development [20]. Indeed, this goal of big data analytics and its application in smarter cities is more in conjunction with the aspiration and intention of the diverse stakeholders that support the integration of big data technology and the associated information sources.

Big data computing

Big data: concept and characteristics

There is no definite definition of big data. Therefore, many definitions have been suggested and are available in the literature, with each tending to offer a particular or different view of the concept based on the context of use and hence serving as, as one way of looking at it, a constituting or complementary aspect of the full picture of the concept. For example, a survey of the emerging literature conducted by Kitchin [79] denotes a number of key characteristic features. Big data are:

- Huge in *volume*, consisting of terabytes or petabytes of data;
- High in velocity, being created in or near real-time;
- Diverse in *variety*, being structured and unstructured in nature, and often temporally and spatially referenced;
- *Exhaustive* in scope, striving to capture entire populations or systems (n = all), or at least much larger sample sizes than would be employed in traditional, small data studies;
- Fine-grained in *resolution*, aiming to be as detailed as possible, and uniquely indexical in identification;

- *Relational* in nature, containing common fields that enable the conjoining of different data sets;
- *Flexible*, holding the traits of extensionality (can add new fields easily) and scaleability (can expand in size rapidly).

A great deal of the existing definitions tend to converge on three main attributes of big data: the huge *volume* of data, the wide *variety* of data types, and the *velocity* at which the data can be collected and analysed. These are identified as the most agreed upon Vs (e.g., [49, 86]). Yet, big data tend to be characterised by a number of other Vs than these three, including inveracity, validity, value, and volatility (e.g., [72]). See Bibri [20] for a descriptive account of these Vs. In the context of this paper, the term 'big data' is essentially used to mean collections of datasets whose volume, velocity, variety, exhaustivity, relationality, and flexibility make it so difficult to manage, process, and analyze the data using the traditional database systems and software techniques. In other words, big data refer to humongous volumes of both structured and unstructured data that cannot be processed and analysed with conventional applications, or that exceed their computational and analytical capabilities. However, as a common thread running through most of the definitions of big data, the associated information assets are, to reiterate, of high-volume, high-variety, and high-velocity, and thus require cost-effective, innovative forms of data processing, analysis, and management. In the context of smart and smarter cities, the term can be used to describe a colossal amount of urban data, typically to the extent that their manipulation, analysis, management, and communication present significant computational, analytical, logistical, integrative, and coordinative challenges. Such data are invariably tagged with spatial and temporal labels, commonly streamed from a large number and variety of sources, and mostly generated automatically and routinely; hence, it is near on impossible to make sense of, or decipher, the big data generated in smart and smarter cities based on computing technology in current use [20]. Therefore, the big data deluge flooding within smart and smarter cities entails rather the use of novel technologies and their integration in terms of algorithms and techniques that are based on supervised and unsupervised learning methods (e.g., classification, clustering, regression, causal modelling, etc.), techniques (e.g., data mining, machine learning, statistical analysis, database querying, etc.), and processing platforms (Hadoop, Spark, HBase, MongoDB, etc.) that could work beyond the limits of the existing analytic systems employed to extract useful knowledge from large masses of data for timely and accurate decision-making and enhanced insights.

Big data analytics: concept and characteristics

The term 'big data analytics' denotes 'any vast amount of data that has the potential to be collected, stored, retrieved, integrated, selected, preprocessed, transformed, analyzed, and interpreted for discovering new or extracting useful knowledge. Prior to this, the analytical outcome (the obtained results) can be evaluated and visualised in an understandable format before their deployment for decision-making purposes (e.g., an enhancement of, or a change in, an operation, function, service, design, strategy, or policy). Other computational mechanisms involved in big data analytics include search, sharing, transfer, querying, updating, modelling, and simulation. In the context of sustainable smart and smarter cities, big data analytics refers to a collection of sophisticated and dedicated software applications and database management systems run by machines with very high processing power, which can turn a large amount of urban data into useful knowledge for enhanced, well-informed decision-making and deep insights in relation to various urban domains, such as transport, mobility, traffic, environment, energy, land use, waste management, education, healthcare, public safety, planning and design, and governance' [21, p. 234].

The common types of big data analytics being used in the context of smart and smarter cities are: descriptive, predictive, diagnostic, and prescriptive [20]. They are to be applied to extract useful knowledge of different forms of intelligence from large datasets, which can in turn be used to serve various purposes depending on the urban application domain. As far as the complexity of big data analytics is concerned, it is commonly characterized by four Is, namely (1) In-situ analytics which directly operates on the data where it sits without requiring an expensive process of Extract, Transform, Load (ETL), (2) interactive analysis where the analysts work interactively with data and the subsequent questions are formulated depending on the results of the previous ones, (3) incremental analysis which requires maintaining models under high data arrival rates and datasets be interactively analyzed based on the previous results, and (4) iterative analysis which iterates over the data several times in order to build and train a model of the data (e.g., predictive data mining) rather than just extract data summaries or make grouping (e.g., descriptive data mining).

Big data processing platforms

There exist many data processing platforms that can be used to perform big data analytics in terms of storage, manipulation, management, analysis, and evaluation of large masses of data to extract useful knowledge deployable in the form of intelligence in relation to various urban domains as to operations, functions, strategies, designs, and policies. The use and implementation of such platforms depend, or vary based, on several factors pertaining to the computational, analytical, logistic, integrative, and coordinative requirements of big data projects as well as their objectives (e.g., environmental sustainability, social sustainability, public services, etc.). Among the existing data processing platforms being used in smart and smarter cities based on cloud computing and fog/edge computing (see [21] for a detailed account and comparison of these two models) include Hadoop MapReduce, Spark, Stratosphere, and NoSQL-database system management (e.g., [5, 20, 49, 69, 73, 115]). These platforms 'perform big data analytics related to a wide variety of large-scale applications intended for different uses associated with the process of sustainable urban development, such as management, control, optimisation, assessment, and improvement, thereby spanning a variety of urban domains and sub-domains… Thus, they are prerequisite for data-centric applications in the context of sustainable smart and smarter cities' [21, p. 203].

Underpinning technologies

As a new paradigm, big data computing amalgamates, as underpinning technologies, large-scale computation as well as new data-intensive techniques and algorithms and advanced mathematical models to build and perform data analytics. It demands a huge storage and computing power for data curation and processing for the purpose of discovering new or extracting useful knowledge typically intended for immediate use in an array of multitudinous decision-making processes to achieve different purposes. It entails the following components, of which [23] provides a descriptive account:

- Advanced techniques based on data science fundamental concepts and computer science methods.
- Data mining models.
- Computational mechanisms involving such sophisticated and dedicated software applications and database management systems.
- Advanced data mining tasks and algorithms.
- Modeling and simulation approaches and prediction and optimization methods.
- Data processing platforms.
- Cloud and fog computing models.

Big data application

Big data analytics has become a key component of the ICT infrastructure of smart and smarter cities due to its role in improving sustainability, resilience, efficiency, and the quality of life (e.g., [5, 6, 16, 20–22, 25, 26, 54, 83]) through effective decision-making processes and thus desired outcomes. In this context, it targets the intelligent decision support and optimisation and simulation associated with the operational functioning, planning, design, and development of urban systems as operating and organizing processes of urban life in terms of control, automation, management, efficiency, enhancement, and prediction as urban intelligence functions. One example of such functions concerns the provision of ecosystem services and the delivery of human services, as well as the effectiveness of strategies and policies based on emerging trends and shifts, in line with the long-term goals of sustainability [20]. The target of big data analytics entails the implementation of decision-taking processes, optimization strategies, and simulation models. All in all, there is a growing consensus that big data analytics and its application will create and enable, in light of the projected advancements and innovations within related platforms, techniques, processes, and methods, immense possibilities and fascinating opportunities in the near future.

A detailed survey of relevant work: issues, debates, gaps, benefits, challenges, opportunities, and prospects

Smart and smarter cities

Research strands from a general perspective

In the field of smart and smarter cities, research in its various forms is inherently interdisciplinary and transdisciplinary and remarkably heterogeneous in terms of programs and endeavours. As such, it involves a plethora of issues, debates, challenges, risks, impacts, benefits, opportunities, prospects, trends, global shifts, and practices, or an amalgamation of these. In this respect, the topic of smart and smarter cities brings together a wide variety and large number of studies, including research directed at conceptual, theoretical, applied theoretical, analytical, empirical, practical, discursive, futuristic, visionary, socio-technical, and so on with such directions as computational, technical, technological, architectural, environmental, spatial, social, political, cultural, institutional, economic, and overarching. Indeed, the recent years have witnessed a great interest in, and a proliferation of publications and scientific writings on, the topic of smart and smarter cities from diverse multi-perspectival approaches, reflecting the magnitude, breadth, depth, and heterogeneity of research within the field [20, 25]. This continues to rapidly and dynamically evolve with varied and new emphases and aims, as well as with more integrated and holistic approaches, manifested in the miscellaneous contributions being, and will continue to be, made or produced by a great deal of researchers, scholars, academics, planners, and experts to the conceptualisation, design, development, and implementation of smart and smarter cities and related future visions. In all, the field of smart and smarter cities merges broad streams of scholarship, which entail many research strands, and as the body of literature on smart and smarter cities has evolved remarkably over the past 10 years or so, new social issues and concerns have been brought to the analysis, and new uses of technology and their ends have been proposed and criticised, respectively. Speaking of such issues and concerns, to note, the challenge is that, as pointed out by Lytras and Visvizi [89], research originating in the social sciences tends to reduce the centrality of ICT in smart city research, and hence, the depth and breadth of implications that emerge at the intersection of ICT in urban spaces and innate social problems remain underexplored.

In a recent extensive interdisciplinary literature review [25], provide a comprehensive review of the field of smart and smarter cities in terms of the underlying foundations and assumptions, state-of-the art research and development, research opportunities and horizons, emerging scientific and technological trends, and future planning practices. There are several research strands addressed in their review, which can be seen from a general perspective in the context of this paper. Theses strands (supported by recent research) are presented below:

Theory and practice The theory and practice of urban computing, urban ICT, and urban science and related sub-areas (e.g., data sensing, big data analytics, context-aware computing, urban informatics, cloud computing, fog/edge computing, middleware infrastructures, intelligence functions, simulation models, database management and integration, wireless communication networks, decision-support systems, etc.) and their relation to the operational functioning, management, planning, development, and implementation of smart and smarter cities with respect to such diverse urban domains as energy, natural environment, built environment, transport, mobility, traffic, water, waste, design, education, healthcare, public safety, governance, economy, and science and innovation. The main focus of this strand of research is on the advancement, use, and application of ICT of ubiquitous computing for optimisation, control, automation, management, and assessment purposes, particularly in relation to economic development, service delivery, and the quality of life. Owing to its origins, smart and smarter city research remains dominated by analytical perspectives and applicable insights from broadly conceived ICT of pervasive computing. Even though smart and smarter city research has, over the past few decades, transformed into a multidisciplinary, interdisciplinary, and transdisciplinary field, housing, integrating, and fusing a variety of domains and disciplines, it is still heavily based on computer science and engineering, with an explicit focus on how advanced technologies and their applications and services may be applied in urban environments [22, 89].

Conceptual and theoretical work The body of the conceptual and theoretical work focuses on developing and examining the existing definitions and theoretical models to provide both a shared conceptualisation and understanding of smart and smarter cities as well as a basis for discussions or debates on what the smart and smarter city approach aspires or claims to deliver with respect to smartness and sustainability and their integration and synergy. The second part of this strand of research focuses further on the theories and academic discourses underpinning the thinking about and the conception of the subject and phenomenon of smart and smarter cities. It is concerned with analysing the discourse of smart urban development and discussing how diverse political mechanisms and policy measures are devised and implemented to institutionalise this discourse, and therefore make it function and culturally and publicly disseminate it, as well as how the ensuing decisions are made in relation to the implementation of ICT and its use for operationalising smart urban development. Among the issues related to this strand of research involve the definition of theoretical terms and models and the creation of discursive notions and constructions along with different understandings, adding to how these underlying issues are germane to the subject of smart and smarter cities. Accordingly, 'this subject has a theoretical base that is open to interpretation, evaluation, and examination, or in it, theoretical debate seems to be rife and a key aspect of the discipline of smart urban planning and development. Having a practical application, the subject of city within this discipline relies on theoretical assumptions and foundations. And it requires environmental, social, cultural, economic, and physical issues to be addressed…, as well as institutional priorities and technological considerations…to be set apart from theoretical matters of urban planning and development as internally consistent models… In all, this strand of research is concerned with comparing and evaluating concepts and approaches, weighing up arguments, rethinking issues, and challenging discursive assumptions' [25, p. 15].

Analytical work The analytical work investigates propositions about what makes a new city badges itself, and an existing city regenerates itself, as smart, or what shows that a city is manifestly planning to become smart, as well as the extent to which a modern city uses advanced ICT to fashion advanced urban intelligence functions and simulation models pertaining to different domains and thus directed for various purposes. This strand of research covers descriptions, elaborations, assessments, and/or classifications of smart and smarter cities based on the use and application of emerging and future ICT in relation to operations, functions, services, designs, strategies, and policies by analysing previous and ongoing projects, initiatives, and programs and their potential effects on the different aspects of urbanity. The recent propositions being investigated tend to put an emphasis on specific technologies (e.g., big data analytics, context-aware computing, cloud and fog computing, etc.) and their novel applications and services, along with the challenges involved in achieving various smart and smarter city statuses accordingly.

Advanced ICT impacts The impacts advanced ICT can have on how we think about and conceive of cities in the sense that the technology propels us to rethink or alter some of the fundamental or established concepts and approaches through which we understand, analyse, operate, organise, assess, and value urban life towards creating and discovering novel ways of living and working in the city and interacting with the environments in terms of, for example, sustainability. Here, the argument is that smart and smarter cities may thrive further or get smarter by leveraging their informational landscape in ways that allow to improve and maintain their contribution to the goals of sustainable development. This is due to the fact that ICT is founded on the application of data science and complexity science, which are well positioned to tackle the complex challenges of urbanisation and sustainability. The focus in this context is on understanding the link between the smart and smarter city technologies and their pertinence for providing innovative solutions for sustainability. In this case, the cities standing on a smartness scale spectrum can well embrace and pursue the goals of sustainable development through related initiatives, programs, and projects, and thereby achieve the required level of sustainability as to operations, functions, services, strategies, designs, and policies within urban domains.

Deficiencies and misunderstandings pertaining to sustainability The emphasis in this strand of research is on the lack or week connection between smart cities and sustainable cities, and whether or the extent to which the concept of smart and smarter city incorporates the goals of sustainable development. In this regard, it has been argued that the existing definitions of smart and smarter city set up no baseline for sustainability, and do not include what sustainable development entails, although defining this concept is of crucial importance for identifying and specifying the purpose for which smart solutions should be used and applied, and also for assessing whether or the degree to which such solutions contribute to sustainability. In fact, the concept of smart and smarter city seems to say little about the manner in which the substance behind the smart solutions is linked to the goals of sustainable development, especially in relation to environmental sustainability.

A recent research wave has started to investigate technological propositions about what makes cities particularly smarter in terms of achieving the goals of environmental sustainability; however, these propositions are too often, if not always, mentioned without consideration of the rather established strategies (design concepts and principles and planning practices) through which environmental urban sustainability can be achieved, namely density, diversity, compactness, and mixed-land use, as well as ecological design, passive solar design, and sustainable transportation, in addition to environmental management and control, environmental policy, renewable energy, and design coding. The underlying premise is that ICT as an integrative and constitutive technology can make a substantial contribution to enhancing the outcome of these strategies if planned strategically and its implementation is directed for the purpose in the context of smart and smarter cities. The way forward is to adopt the cutting-edge solutions being offered by big data analytics and its novel applications and services associated with environmental sustainability. This strand of research is also part of, and hence, related issues are examined and discussed in, the next section given their high relevance to the topic of this study.

Scientific challenges The scientific challenges facing smart cities of the future or smarter cities and pertaining to the use and application of emerging and future technologies such as big data analytics and its novel applications. Such challenges include, but are not limited to, the monitoring of urban infrastructure and its connection with its operational functioning, planning, and development through control, automation, optimisation, management, and simulation; the exploration of the idea of smart and smarter cities as innovation labs in terms of developing and applying intelligence functions across different urban domains; the construction and aggregation of many urban simulation models pertaining to various urban systems and domains in terms of their integration and coordination, respectively, and thereby providing portfolios of such models that inform future designs; the development of effective technologies that ensure equity and fairness and improve the quality of city life; the optimisation of physical mobility and the improvement of virtual mobility for reducing environmental impacts and enhancing spatial and non-spatial accessibility to opportunities, services, and facilities for citizens; the creation of technologies that enhance citizen participation and engagement as well as create shared knowledge for democratic governance.

Potential risks of ICT to sustainability This strand of research looks at the negative implications of the development and implementation of smart and smarter cities in terms of the design, use, application, and disposal of ICT for environmental and social sustainability. Smart and smarter cities pose significant risks to the environment due to the massive use of ICT of pervasive computing. Driving this line of research is a set of questions addressing the way smart and smarter cities should measure and identify risks, uncertainties, and hazards associated with ICT use and set safety standards accordingly, i.e., sustainable design principles and environmental policies. The involved risks of ICT go beyond environmental sustainability to include social sustainability in terms of equity, fairness, participation, inclusion, privacy, security, and so on. In particular, it is important to address the digital divides pertaining to education, age, social status, culture, ethnicity, gender, and disability. Angelidou [9] found that most smart city strategies are poorly adapted to accommodate the local needs of their area, fail to incorporate bottom-up approaches, and fall short in considering issues of privacy and security. In a recent work, Carrasco-Sáez et al. [31] propose a new pyramid of needs for the digital citizens as a way of transitioning towards smart human cities or socially sustainable smart cities. Regardless, socio-economic factors affect the use of smart technologies, and to fully optimise their potential, such factors need to be addressed so that smart and smarter city technologies can play a part in contributing to sustainability. As stated by Batty et al. [16], 'New technologies have a tendency to polarise and divide at many levels and we need to explore how new forms of regulation at the level of urban transport and planning, and economic and community development can be improved using future and emerging technologies'. And one way this can be accomplished is by, according to the authors, balancing efficiency and equity. For a detailed account and discussion on the relevant digital gaps associated with ICT of pervasive computing, the interested reader can be directed to Bibri [19]. Visvizi and Lytras [134] address the role of policy in making smart cities more socially inclusive. Further, however, the most eminent threat of ICT in the context of smart and smarter cities lies in its multidimensional effects on the environment, as ICT as an enabling, Integrative, and constitutive technology is embedded into a much wider socio-technical landscape (economy, institutions, policy, politics, and social values) in which a range of factors and actors other than techno-scientific ones are involved. In addition, the prospect of smarter cities as future visions of smart cities is becoming increasingly the new reality with the massive proliferation of the core enabling technologies of ICT of pervasive computing across urban systems, domains, and environments. Indeed, they typically instantiate the dominating ICT visions in Europe, Asia, and the USA, namely Ubiquitous Computing, Ambient Intelligence, and the Internet of Things. The evolvement of this smart urban development approach is increasingly driven by the growing application of, and the rising demand for, big data analytics and its novel applications and services as a set of novel technologies. Of importance to underscore in this regard, though, is that these technologies need to be well understood when placing high expectations on and marshalling huge resources for developing and deploying smarter cities or smart cities of the future. There exist intricate tradeoffs and relationships between and among the positive impacts, negative effects, and unintended consequences of ICT of pervasive computing in relation to the environment—flowing mostly from the design, development, use, application, and disposal of ICT throughout smart and smarter cities [20]. Nevertheless, there are several potential ways to mitigate the potential risks pertaining to the development of ICT of pervasive computing and thus smart and smarter cities. Especially, most of the related novel applications are still under development, and thus, a lot more can be done in this direction prior to their deployment. It remains to see the extent to which new technological innovation opportunities will be embraced and exploited in this regard, and their effects be realised with regard to environmental sustainability in the context of smarter cities or smart cities of the future, in particular. Bibri [20] provides a detailed overview and discussion of the key technical, social, political, institutional, and organisational remedies to deal with the multiple effects triggered by, and associated with, the design, use, application, and disposal of ICT, including direct and indirect effects, rebound effects, systemic effects, and constitutive effects. See Bibri and Krogstie [24] for a detailed discussion. These remain, however, complex and intricate and thus problematic to tackle. Regardless, it is high time to link ICT research, development, and innovation with the agenda of sustainable development and thus to justify future ICT investments by environmental concerns and socio-economic needs in the context of smarter cities or smart cities of the future.

Frameworks, models, and infrastructures The smart and smarter city frameworks, models, and infrastructures are associated with the assessment, development, and implementation of smart and smarter cities, and are shaped by socio-cultural factors, technological capabilities, available resources, regulatory policies, institutional practices, and so on. The existing frameworks and models are being used to rank or benchmark the existing and emerging smart and smarter cities in relation to smartness and sustainability as well as their synergy and integration. They are based on a variety of dimensions with a set of factors or criteria gauging success, including mobility, environment, energy, transport, life quality, economy, and governance. The existing infrastructures involve the different aspects of ICT in terms of its development and implementation in smart and smarter cities (e.g., sensor technologies, data processing platforms, cloud and fog computing models, wireless communication networks, middleware infrastructures, etc.). The purpose is to provide a smart and smarter city basic backbone for enabling ICT-based control, automation, optimisation, management, and planning, as well as privacy and security in relation to urban operations, functions, services, designs, and policies.

All in all, the state of the scholarly research within the rapidly burgeoning interdisciplinary and transdisciplinary field of smart and smarter cities shows that the large body of the topical studies carried out thus far tend to focus largely on the advancement and potential of emerging and future technologies and their novel applications and services as new opportunities offering numerous benefits and robust solutions. This relates to diverse urban domains in terms of enhancing the efficiency of urban systems and improving the quality of life of citizens. However, the rapid pace of ICT development and innovation seems to happen ad hoc when new technologies and their applications and services become available—rather than grounded in a focused overall approach or directed to solving the most pressing issues and significant challenges associated with sustainability in an increasingly urbanised world. Indeed, more efforts need to be done for developing and implementing the kind of smart solutions that are oriented towards addressing, or for a realistic tackle of, environmental concerns and socio-economic needs, especially in the context of smarter cities or smart cities of the future. Findings from a recent study carried out by Angelidou et al. [6] suggest that the smart city and sustainable city landscapes are extremely fragmented both on the technological and policy levels, and that there is a host of unexplored opportunities and horizons toward new approaches to sustainable smart development, many of which are still unknown. Moreover, the research field of smart and smarter cities is currently fragmented due to its ill-defined character and scattered research programs, thereby fostering discontinuity, and consequently, smart perspectives remain too diverse to resolve [20]. At the practical level, to add, there is a great deal of diversity among smart and smarter cities in terms of the previous and ongoing projects and initiatives. And in this sense, it is of relevance to look at the smart and smarter city endeavour as an ambition which can be driven by a wide range of target objectives as well as available resources, technical capabilities, and policy regulations, and also shaped by diverse disruptive technologies and how these are embedded in the socio-cultural context as part of the socio-technical landscape. Obviously, there will be multiple ways to achieve such objectives, manage available resources, design and execute policy regulations. This should have direct implications for the success of smart and smarter cities, including in relation to their sustainability performance and its continuation.

Research strands of particular relevance to the topic of the study

The topic of this study entails other relevant research strands than the above mentioned ones in terms of review. These strands are also part of the broad streams of scholarship that constitute the field of smart and smarter cities. With that in mind, the focus of this subsection is on reviewing the field of smart and smarter cities in relation to sustainability and related big data applications.

The inadequate contribution of smart cities of today to the goals of sustainable development and thus their poor sustainability performance Since its adoption in urban planning and development in 1994 until recent years, the concept of smart city has been criticised for not explicitly incorporating the goals of sustainable development in its definition, as well as for lacking the connection with that of sustainable city (e.g., [2, 6, 20, 25, 28, 55, 56]). According to a recent study carried out by Ahvenniemi et al. [2] on the difference between smart cities and sustainable cities, in the former economic and social aspects tend to dominate over environmental aspects. Also, Kramers et al. [82] point out that the concept of smart city says little about the environmental sustainability performance of cities. Moreover, in examining the concept of smart city through the lens of strategic sustainable development, Colldahl et al. [37] conclude that this concept is associated with limitations pertaining to sustainability, i.e., 'does not necessarily allow for cities to develop in a sustainable manner'. Therefore, Ahvenniemi et al. [2] suggest a redefinition of the smart city concept towards a more integrated direction, a definition that highlights the dimension of environmental sustainability. Furthermore, Bibri [23] notes that the contribution of smart cities to sustainable development remains vague. In relation to this, while some of the challenges pertaining to urbanisation are already being addressed through the development of smart technologies [29, 40, 133], many of the proposed smart solutions in this regard are not aligned with sustainability targets, thereby the emergence of sustainable smart cities [2, 20]. Overall, as concluded by Bibri and Krgostie [25], the existing smart city approaches raise critical issues, pose special conundrums, and involve significant challenges—when it comes to their development and implementation as to their contribution to the goals of sustainable development. In more detail, Bibri [20] provides a detailed review of the field of smart and smarter cities in terms of its state-of-the art research and development and foundations and assumptions, and presents a tabulated version of his discussion on the shortcomings of smart cities in terms of sustainability performance. Among the points mentioned and that are of more relevance to the topic of this study are presented below:

- There is no general consensus about whether there needs to be any substance behind the claim of smartness for, or how it is linked to, sustainability.
- Smart technologies are less focused on providing solutions for the challenges and pressing issues related to sustainability and more focused on optimising the efficiency of solutions.
- There is a discrepancy between smart solutions and sustainability problems.
- There particularly is a weak connection between smart solutions and environmental problems.
- There is a mismatch between smart targets and sustainability goals.
- There are gaps between theory and practice and visions and their realisation with regard to the sustainability dimension.
- Current ICT investments and technological innovation orientations fall short in considering or embracing the goals of sustainable development.

- The field is unable to proceed in anything like a cumulative fashion and to contribute systematically and constructively to the development of innovative technologies for sustainability.
- Smart technologies mostly provide pre-configured/pre-formatted solutions for yet-to-find urban problems, rather than the needed solutions for tackling the challenge of sustainability.
- ICT research, development, and application are directed mainly towards economic development.
- There are divergences in terms of the current and future use of big data applications, as well as in terms of related innovation.
- The existing assessment performance frameworks lack environmental indicators and tend to overemphasise economic aspects.
- ICT poses great risks to and negative implications for environmental and social sustainability.

Furthermore, concerning the lack of connection, integration, and synergy between smart cities and sustainable cities, Bibri and Krogstie [25] provide a list of the key discrepancies in this regard, which include in relevance to the topic of this paper:

- Smart cities focus mostly on ICT advancement and the efficiency of solutions and fall short in considering, if not ignoring, design concepts and principles and planning practices of urban sustainability and their effects and benefits.
- Smart cities continue to strive for smart targets rather than integrating them with sustainability goals.
- Sustainability goals and smartness targets are misunderstood as to their interconnection.
- The two landscapes of the smart city and sustainable city are extremely fragmented on the technical and policy levels.
- Smart cities need to leverage their informational landscape together with their physical landscape in line with the vision of sustainability.
- Smart technologies are still being developed for building and enabling smart cities without any orientation towards, or any consideration of, improving the contribution to the goals of sustainable development.
- The existing smart city performance assessment frameworks need to be redeveloped in ways that incorporate the design concepts and principles and planning practices of sustainability as well as environmental indicators.

In relation to the latter point, while a recent wave of research work has started to focus on various technological propositions about what makes cities smart and smarter as to contributing to, or achieving, the goals of sustainable development [25], such propositions are too often investigated without consideration of the rather established strategies for achieving urban sustainability, specifically design concepts and principles and planning practices, such as compactness, mixed-land use, density, diversity, passive solar design, sustainable transport, ecological design, and design coding. In line with this, Angelidou et al. [6] conclude that there is a host of unexplored opportunities towards new approaches to sustainable smart development as a way to address and overcome the existing fragmentation between smart cities and sustainable cities pertaining especially to the technical level. Of importance to underscore here is that for many contemporary urban scholars, theorists, and planners, the adoption of the strategies through which sustainable urban forms can be achieved is necessary for achieving the required level of sustainability (e.g., [42, 62–64, 67, 141, 142]). This is irrespective of how intelligently, by using advanced ICT, urban systems (built environment, infrastructure, ecosystem services, human services, and administration) can be managed and integrated and urban domains (transport, energy, mobility, traffic, water and waste, natural environment, health and safety, education, governance, economy, science and innovation, etc.) can be coordinated and coupled, as well as how these systems and domains can be planned and developed [20, 26]. Rather, cities can well become smartly sustainable pr sustainably smart if the ubiquity and massive use of ICT could primarily be directed towards improving sustainability (e.g., [16, 20, 28, 55, 82, 112]). In this regard, smarter cities remain well positioned for providing the kind of computationally augmented urban environments that can provide the favourable conditions and offer the cutting-edge solutions that are conducive to boosting the process of sustainable development [25]. Overall, regardless of the type of the innovative solutions proposed for enhancing sustainability performance in smart and smarter cities, it is of crucial importance to ensure that urban development initiatives and projects resonate with the significant themes in debates on the design concepts and principles and planning practices pertaining to sustainable urban forms. Bibri [20] provides a detailed account of these themes and propose a matrix linking them with big data applications in the context of smart sustainable cities of the future.

Moreover, Ahvenniemi et al. [2] contrast 8 smart city and 8 sustainable city assessment frameworks as performance measurement systems with respect to 12 application domains as a way to examine how the former compares with the latter regarding both commonalities and differences. They observe a much stronger focus on modern ICT in the former in relation to economic and social aspects and a deficiency in environmental indicators, to reiterate. The 12 application domains included in this study comprise transport; energy; water and waste management; natural environment; built environment; health and safety; education; well-being; and citizen engagement; governance; economy; culture, science and innovation; and ICT, based on 3 impact categories: environmental, economic, and social sustainability, involving 958 indicators altogether. They conclude that smart cities need to improve their sustainability performance with support of advanced technologies. They suggest, based on the main identified gap between the two classes of assessment performance frameworks, the improvement of smart city ones in ways that incorporate and use impact indicators that measure the environmental and social targets of sustainable development, in addition to the economic ones, and thus gauge the contribution of smart cities to sustainability. As indeed noted by Marsal-Llacuna [92], in the academic debate, smart cities are criticised for their focus on the economic dimension of sustainability while disregarding environmental and social dimensions.

In light of the above, smart cities need to direct more efforts into embracing the goals of sustainable development and harnessing their informational assets and physical structures together accordingly so as to mitigate their shortcomings associated with sustainability. This can occur through (re)developing urban environments, areas, and spaces in ways that (re)orientate ICT use and innovation towards contributing to, and enhancing design concepts and principles and planning practices of, sustainability. Especially, several topical studies performed in recent years emphasise the need for pursuing this alternative developmental path for advancing sustainability (e.g., [6, 20, 25, 26]). Smart cities can become sustainable and sustainable cities smart when ICT is primarily utilised for and directed towards enhancing sustainability performance with respect to what each of these two urban development strategies lack in terms of any potential inadequacy as to this performance (e.g., [5, 16, 18, 20, 26, 55, 82, 112]). This pertains mainly to environmental sustainability. Indeed, Ahvenniemi et al. [2] and Angelidou et al. [6] report the misalignment between the targets of smart urban growth and sustainable urban development, with the former stating that smart city assessment frameworks downplay the importance of environmental sustainability, and the latter highlighting the unexplored role of smart applications in advancing environmental sustainability.

Realising the tremendous potential of smart cities of the future for advancing sustainability In the early 2010s, Erdmann and Hilty [44] highlighted the crucial role that ICT could play in sustainable urban development by decoupling resource consumption and environmental impact from economic growth, while noting that the topic of ICT for sustainability had not attracted actionable political interest as of yet. In looking at smart cities through the lens of strategic sustainable development, Colldahl et al. [37] note that smart cities hold great potential for advancing sustainability, as it is a powerful approach to enabling cities to become more sustainable due to the role of ICT in providing advanced solutions for addressing the complex challenges and pressing issues of sustainability, in addition to planning cities in a more innovative and forward-thinking manner. In reference to smart cities of the future, Batty et al. [16] point out that cities can only be smart if there are intelligence functions that are able to integrate and synthesise the data to some purpose, ways of improving efficiency, sustainability, equity, and the quality of life. Future ICT in its form of big data analytics and its application is concerned with researching smart cities not simply in terms of their instrumentation: 'constellations of instruments across many scales that are connected through multiple networks which provide continuous data regarding the movements of people and materials in terms of the flow of decisions about the physical and social form of the city' [16], but also in terms of the way this instrumentation is opening up new opportunities for and new forms of advancing sustainability.

It is not until very recently that smart sustainable/sustainable smart urban development as an intellectual discourse did elicit and attract great attention among urban scholars, practitioners, and policymakers, as well as ICT experts and computer scientists working within the area of applied urban science or urban informatics, especially in the subfield of big data and its relation to urban analytics, planning, and development. Evolving subsequently into a more powerful and established techno-urban discourse emanates from the fact that the strategic urban actors are increasingly relating to it in a structured way in different contexts of their practices—socially anchored and culturally institutionalised actions [20]. The accordingly increasing insertion, functioning, and dissemination of such discourse is increasingly shaped and influenced by the emerging smart technologies and their future generation being under vigorous investigation and scrutiny by ICT industry consortia, collaborative research institutes, policy networks, and Quadruple Helix of University-Industry-Government–Citizen relations in terms of research, development, and innovation within ecologically and/or technologically advanced nations [20].

Concurrently, the concept of smart sustainable/sustainable smart cities has gained momentum as both a holistic approach to urban development as well as an academic and societal pursuit, not least in technologically and ecologically advanced nations [24]. That is to say, it has become important not only in urban planning and policymaking, but also in urban research and practice, generating worldwide attention as a powerful framework for strategic sustainable urban development [20]. Further, this concept has emerged as a result of three important global trends at play across the world, namely the rise of ICT, the diffusion of sustainability, and the spread of urbanisation [25]. As echoed by Höjer and Wangel [55], the development of ICT, sustainability awareness, and urban growth as interlinked shifts have recently converged under what is labelled 'smart sustainable cities'. Accordingly, such cities represent a new techno-urban phenomenon that materialised around the mid–2010s (e.g., [2, 4, 6, 25, 55, 60, 82, 130]). The underlying idea revolves around leveraging the prevalence and advance of ICT of pervasive computing in the transition towards the needed sustainable development in an increasingly urbanised world [20]. Worth pointing out is that there are several differences between sustainable smart cities and smart sustainable cities. One obvious distinction to highlight is that the former involves those cities that badge themselves as smart and are striving to become sustainable, and this class of cities often relates to technologically advanced nations. The latter entails those cities that badge themselves as sustainable and are striving to improve and maintain their contribution to sustainability using the advanced forms of ICT, and this class of cities pertains to ecologically advanced nations.

However, the development of sustainable smart cities is increasingly gaining traction and pre-eminence worldwide, surpassing all other urban development approaches, especially in the world's major cities, supported by policymakers, governments, research institutions, universities, and industries. Given the apparent relevance and usefulness of the findings produced in the field of smart cities, the related research and development has been embraced and advocated by the United Nations (UN), the European Union (EU), and the Organisation for Economic Co-operation and Development (OECD) (e.g., [89]). For example, a common understanding shared by the European Commission and reflected in the Smart Cities and Communities European Innovation Partnership (SCCEIP) is that smart technologies in their various forms hold great potential for achieving sustainability in smart cities, particularly in relation to the intersection between energy, transport, and ICT, where the associated industries have been invited to collaborate with cities to address their challenges and needs [47]. This will enable innovative, integrated, and efficient technologies to roll out and enter the market more smoothly, making cities the nexus of innovation [47]. Accordingly, the European Union's policies highlight the synergy between smart technologies and sustainable urban development, as manifested additionally by the EU's current 10-year development strategy through which the objectives of fostering smart, inclusive, and sustainable development in Europe were set, and at the heart of which innovation is seen as a means to tackle the environmental challenges associated with climate change and intensive energy use and its inefficiency. Moreover, recent research and policy reports highlight synergies and benefits at the intersection of smart and sustainable urban development [6]. The most widely cited report of the World Urbanisation Prospects series of the United Nations [126] clearly states that this trend of integrating both urban development paradigms in terms of polices and practices will continue to rise at least up to 2050, highlighting the growing role of ICT in mitigating the rising challenges of sustainability. As stated in the report, the policy implications drawn from this study include the use of ICT in facilitating a sustainable mode of urbanisation, one that enhances and efficiently delivers services to diverse urban stakeholders, as well as the necessity to have accurate, consistent, and timely data to inform city-related policy-making, among others. The United Nations has already begun to explore the role of big data for sustainable development in the form of action-oriented research in that direction [127].

In addition, many governments have recently set ambitious targets to transition their cities to being sustainable smart using a variety of initiatives and programs, or have adopted the concept of smart city and implemented big data applications to reach the required level of sustainability and to improve the living standards. Accordingly, it has become of crucial importance to develop and utilise new methods for measuring the performance of sustainable smartness (e.g., [36, 61, 139]). This is due to the growing realisation of the untapped potential of the emerging smart technologies, especially big data analytics and its application, for addressing the challenges of sustainability and containing the effects of urbanisation.

While there is a growing interest in this flourishing field of research, the academic discourse on sustainable smart urban development within the relevant literature is still scant and also heavily weak on empirical grounding—yet rapidly burgeoning [25]. Indeed, a few studies exploring the subject of sustainable smart cities have been published in the mainstream journals. The case is evidently different from smart cities as an urban development strategy that has been around for more than two decades or so, thereby witnessing a proliferation of academic publications and scientific writings and thus demonstrating a large body of successful practices. However, the extent to which the field of sustainable smart cities is blossoming gives a clear indication of its future developmental path and research direction. In fact, this field of research has materialised in response to the need for overcoming the numerous challenges and issues pertaining to the existing approaches to smart cities with regard to sustainability and urbanisation, as adequately discussed in the previous section.

The research on sustainable smart and smarter cities is garnering increased attention, and its status is consolidating as one of the fanciest and fertile areas of research today. This hot topic and recent wave of research has started to highlight and explore, respectively, the growing significance and role of the advanced forms of ICT in increasing the contribution of smart and smarter cities to the goals of sustainable development. This research wave has become more established about two decades or so after the adoption of the concept of smart city in the domain of urban planning and development in 1994, and in parallel with the emergence and success of the aforementioned discourse of sustainable smart urban development. Explicitly, when this concept has become widespread and mature, and concurrently, most of the core enabling technologies (sensor technology, cloud computing, fog computing, distributed computing, data processing platforms, wireless communication networks, etc.) of smart and smarter cities have become relatively financially affordable, technically advanced, and widely deployed across urban environments. This has been enabled and fuelled by the most prevalent ICT visions of pervasive computing becoming deployable and achievable computing paradigms and thus the new reality in different parts of the world, especially Europe, Asia, and the USA. This new paradigmatic shift in computing as heralding a drastic change in ICT in its various forms and thereby giving rise to innovative solutions and sophisticated approaches increasingly pervading urban domains and environments has made the vision of building and living in sustainable smart cities an achievable and attainable reality [24]. Other driving factors for, or global shifts triggering, the wave of research and phenomenon in question, in addition to the rise, advance, prevalence, and convergence of ICT, is the unprecedented urbanisation of the world's population and the rising concerns over its multidimensional effects, coupled with the mounting challenges of urban sustainability [20]. In particular, as pointed out by Angelidou et al. [6], what has brought the two disciplines of smart urban growth and sustainable urban development closer than ever before, despite the different development trajectories followed until recently, is the growing realisation of the role of technological advancements in monitoring urban environments and making well-informed technical and policy decisions, as well as in reducing resource consumption whose unsustainability is bringing humanity closer to a future where basic goods will be unavailable to large parts of the population. In all, research on sustainable smart cities has attracted attention and evolved on the basis of these different, yet related, developments: smart cities, sustainable cities, ICT of pervasive computing, sustainable development, sustainability, and urbanisation.

Consequently, smart cities have gained traction among particularly many national governments and international policymakers as a promising response to the challenges of sustainable development in an increasingly technologised and computerised, yet unsustainable, urbanised world [20]. It is of particular relevance here to emphasise that it is not until more recently that the development of smart cities came to the fore as a sort of panacea for solving the kind of wicked and intractable problems that characterise the urban domain—thanks to the advent of big data analytics as a set of advanced technologies, coupled with the recognition of the untapped potential of their novel applications and services for advancing various aspects of sustainability (e.g., [5, 16, 18, 20, 93]). Worth noting is that ICT has in fact gained the recognition of offering unsurpassed ways to deal with the environmental, societal, and economic concerns of cities and hence to transform them into urban areas that can adapt to environmental, societal, and economic shocks since the mid 1990s, a few years after the widespread diffusion of the concept of sustainable development and the prevalence of ICT worldwide. Ever since, ICT has been socially and discursively constructed as having an enabling and catalytic role in sustainable development and in envisioning its future form in the context of sustainable smart cities [24]. In smart cities, ICT is proposed as a set of solutions to urban challenges and issues of a complex nature, including sustainability and living standards [16, 54]. In other words, and more detail, smart cities represent an urban development paradigm that emerged in the late twentieth century as a result of the drive of cities to be more responsive to citizen needs through offering conditions conducive to promoting and enhancing the quality of life in an increasingly globalised world [6], and then to become more sustainable in an increasingly urbanised world [60, 130] with support of advanced ICT.

The assessment of smart cities builds on 'the previous experiences of measuring environmentally friendly and livable cities, embracing the concepts of sustainability and quality of life but with the important and significant addition of technological and informational components' [93], cited in [2]. This relates particularly to big data technology and its diverse applications and services, which span many urban domains with regard to improving operational functioning, monitoring and optimising infrastructures and facilities, reducing resource consumption, providing efficient and faster services to citizens to enhance the quality of their life, and streamlining planning and decision-making processes, all in line with the goals of sustainable development [20]. By means of ICT innovations and thus advanced smart solutions, cities can well evolve in ways that can address environmental concerns and respond to socio-economic needs in a more strategic manner, as they are the incubators, generators, and transmitters of creative and innovative ideas [25]. Indeed, the clear prospects of many major cities to overcome the complex challenges pertaining to sustainability and urbanisation through the advanced forms of ICT is the key reason why smart cities of the future has recently gained traction as a holistic urban development strategy among universities, research instituters, policy makers, city governments, and industries. Besides, when discussing ICT solutions for improving the different aspects of sustainability, reference is made to smart cities of the future or smarter cities (e.g., [16, 20]) This is predicated on the assumption that ICT of pervasive computing offers great opportunities for monitoring, understanding, and analysing various aspects of urbanity for operating, managing, and planning urban systems in ways that can be leveraged in the needed transition towards, and the advancement of, sustainability. It is in smart cities of the future that the key to a better world—which is held by emerging and future ICT—will be most evidently demonstrated [16]. The underlying premise is that the use of ICT of pervasive computing and related big data analytics and its application is increasingly contributing to the further integration of urban systems and the effective assessment of their performance in terms of sustainability; facilitating collaboration and coordination among urban domains for energy and environmental efficiency gains; enhancing and mainstreaming ecosystem and public and social services; and pinpointing which kinds of networks need to be coupled or amalgamated. This is due to the merging wave of urban analytics for which big data constitute the fundamental ingredient, thanks to the opportunity of fashioning and utilising powerful intelligence and planning functions and simulation models in relation to urban monitoring, planning, and design [20]. In the meantime, the promises of smart cities is leading to an exponential increase in data by several orders of magnitude. Worth pointing out is that most of the sustainability benefits and opportunities of smart cities tend to be associated with what is labeled 'smarter cities'.

Smarter cities: characteristic features, social shaping aspects, and current issues of and future potentials for sustainability Smarter cities typically rely on the fulfilment of the prevalent ICT visions of pervasive computing, namely Ubiquitous Computing, Ambient Intelligence, Sentient Computing, and the Internet of Things. See Bibri [20] for a descriptive account of these visions. Big data analytics is one of the key prerequisite technologies for realising these visions in terms of the novel applications and services being in use in a wide variety of urban domains, such as transport, mobility, traffic, energy, environment, power grid, building, planning, design, governance, scientific research, innovation, and so on, to improve sustainability. Recent discoveries in computer science and its advanced ICT applications have given rise to those socially disruptive technologies and thus ubiquitous cities, ambient cities, sentient cities, cities as Internet-of-everything, and real-time cities. Of importance to note is that the orientation of these cities towards sustainability through embracing and incorporating the goals of sustainable development as part of national urban development initiatives and projects within technologically and ecologically advanced nations is considered as a new research endeavour that aims to leverage the informational landscape of smart cities in the needed transition towards sustainability [20]. In addition, these cities are associated with the core characteristic features of the future vision of technology in the sense that everyday objects communicate with each other and their surroundings in various ways and collaborate across heterogeneous and distributed environments to provide valuable information and limitless services in the form of intelligence to multiple, diverse urban entities in connection with operations, functions, activities, designs, strategies, and policies. For what this vision entails, the prospect of smarter cities is becoming the new reality with the massive proliferation of the core enabling technologies underlying ICT of pervasive computing [113]. Enabling diverse computationally augmented urban environments in modern cities and seeking to connect city constituents with each other together with their environments, the underlying technologies will enable different kinds of big data applications to usher in nearly very urban domain, thereby opening up new windows of opportunity for enhancing sustainability performance.

Visions of future advances in science and technology (S&T) (and predominately computer science and ICT) inevitably bring with them wide-ranging common visions on how societies and hence cities as social fabrics will evolve in the future, as well as the immense opportunities this future will bring [24]. This relates to the role of science-based technology in modern society in terms of its development, a subject area which is positioned within the research and academic field of Science, Technology, and Society (STS). This is concerned with the ways in which new technology emerges from different perspectives, why it becomes institutionalised and interwoven with politics and policy—cultural dissemination, as well as the risks it poses to environmental and social sustainability [24]. In this context, however, S&T is associated with ICT of pervasive computing and the increasing role it plays in advancing sustainability within contemporary cities. This rapidly evolving form of S&T and related role in sustainable smart cities has recently permeated urban and academic debates as well as politics and policy across the globe, as mentioned and documented above, and is accordingly seen as key for solving the environmental and socio-economic challenges pertaining to sustainability and urbanisation facing modern and future cities. ICT of pervasive computing is drastically changing long-standing forms of city structures, systems, and processes, and revolutionising city transformation models in terms of sustainability and the quality of life [16, 20]. In particular, major urban transformations are promised as a result of the advent of big data analytics and its application as an instance of ICT of pervasive computing. The existing evidence (e.g., [5, 6, 18, 20]) already lends itself to the argument that the use of big data technology and its novel applications across various urban domains makes this technology a salient factor for improving the goals of sustainable development and thereby advancing sustainability. If its research, development, and innovation continue further to be linked with the agenda of sustainable development and the goals of sustainability, i.e., to be utilised meaningfully and strategically, ICT of pervasive computing will have positive, profound, and long-term impacts on smarter cities or smart cities of the future. It is projected to yield hitherto unrealised environmental gains and socio-economic benefits, owing to its technological superiority in terms of the novel applications and services that provide high performance and concrete value [20].

In light of the above, smart cities are ever-changing and morphing into new faces characterised by the profusion of data and massive use of its analytics and related applications. This has been fuelled by the modern world becoming rapidly technologised and hence fully computerised. Adding to this is the increasing convergence and advance of ICT as a powerful enabler and driver for ecological modernisation and societal transformation, thereby playing a key role in addressing and overcoming the challenges of sustainability and containing the effects of urbanisation [24]. At the heart of ecological modernisation as an analytical approach, policy strategy, environmental discourse, and academic field is an established view of the potential of ICT innovations to bring about advanced solutions to complex environmental problems. Ecological modernisation as a theoretical concept is used to analyse those shifts in 'the central institutions and core practices of modern society deemed necessary to solve, avoid, or mitigate the ecological crisis' [19, p. 35]. One of its key dimensions is technology and the transformation of society [100], meaning particularly that environmental problems are most likely to be tackled through the development and application of advanced sophisticated technologies [100], such as big data analytics and related applications. Several ideas arising from the intended ecological switchover have gained footholds in the context of smart cities of the future. Indeed, the pertinence of such cities with that of environmental sustainability is reflected in the EU's urban development policy, whereby sustainable technology is seen as an asset toward optimising energy efficiency and thus reducing GHG emissions as well as fostering urban collective intelligence and innovation [48].

From a societal perspective, ICT is socio-culturally constructed to have a determinant role in instigating major social changes on multiple scales due to its transformational power residing or embodied in its disruptive, synergistic, and substantive effects, coupled with being of an enabling, integrative, and constitutive nature [24]. In relation to this, the coalescence of computing, data processing, and communication technology is unleashing a wealth of opportunities and proving a powerful driver for innovation and change, as well as blurring the boundaries between domains within different societal spheres [59]. In the meta-discourse of the information society and other derived discourses which metonymically represent it, such as smart cities and sustainable smart cities, advanced ICT is seen as a powerful driver for major transformations. As stated by ISTAG [59, p. ii], 'ICT offers a means to respond to many challenges. It is the "constitutive technology" of the first half of this century… ICT does not just enable us to *do* new things; it *shapes* how we do them. It transforms, enriches and becomes an integral part of almost everything we do. As ICT becomes more deeply embedded into the fabric of European society it is starting to unleash massive and far-reaching societal…change. ICT is essential for bringing more advanced solutions for societal problems. These constitutive effects amount to a paradigm shift in how our…society function.' ICT research plays a key role in unlocking the transformational effects of ICT for societal sustainability [59]. It is important not to underplay the radical social transformations that are likely to result from the implementation of ICT visions of pervasive computing [58]. For a detailed analytical account and deep discussion of the diverse dimensions of the social shaping of sustainable smart cities, the interested reader can be directed to Bibri and Krogstie [24].

Smarter cities or smart cities of the future are the product of socio-culturally-conditioned frameworks, including the way the related sustainable practices have emerged and become disseminated at the urban level and hence discursively constructed and materially produced through diverse socio-political institutions and organisations [24]. Therefore, as noted by Bibri [20], smarter cities should not be conceived of as 'isolated islands'; rather, the interplay between them and other scales and their relation to political and regulatory processes on a macro level ought to be recognised. Macro processes of political regulation and policy are deemed of crucial importance for the discursive-material dialectics of smarter cities as urban transformation. In this regard, political action is necessary for the production, insertion, functioning, dissemination, and evolution of smarter cities as an amalgam of innovation systems or a techno-urban discourse. Indeed, political practice is at the core of the theoretical framework of innovation system [32, 70, 71, 109] and the theory of discourse [50]. Recommendations for smarter cities as drastic urban transformations are unlikely to proceed without parallel political actions [116]. Drastic shifts to technological or sustainable regimes 'entail concomitantly radical changes to the socio-technical landscape of politics, institutions, the economy, and social values' [116]. Besides, technology and society and hence cities are shaped at the same time in a mutual process, i.e., the former develops dependently of the latter and then they affect each other and evolve in that process [19]. As succinctly put by McLuhan [97] many decades ago, we shape technology and thereafter it shapes us. This in fact is the kind of challenge that needs to be resolved in the development and implementation of smarter cities with regard to directing ICT towards enhancing their contribution to the goals of sustainable development. To put it differently, the intellectual challenge facing smarter cities lies in that advanced technologies such as big data analytics are not only developed to enable us to shape and alter how we create new and do things in many domains, but also to investigate and assess the processes of their own application and impact on cities as to their concrete contribution to sustainability [20]. Regardless, the way modern cities as complex systems and dynamically changing environments can be operated, managed, developed, and planned requires sophisticated approaches and innovation solutions to understanding and analyse them and to avoid and mitigate potential environmental and social impacts resulting from urban operational functioning, planning, and governance in the context of sustainability, respectively.

The current state of research in the realm of smarter cities shows that not enough focus has been given to the potential of ICT of pervasive computing for responding to the challenges of sustainability and containing the effects of urbanisation [20]. Such cities are mainly striving for smart targets instead of sustainability goals [25], just like current smart cities [2, 93]. In more detail, notwithstanding the relative increase of research on smarter cities—pushed particularly by big data analytics and its application across various urban domains—the bulk of work has tended to deal largely with the advancement of ICT of pervasive computing and its potential only in terms of the use of its novel applications to optimise economic efficiency in terms of productivity, management, cost-effectiveness, and time saving. As well as to improve the quality of life of citizens in regard to better, faster, and more efficient services. This leaves more relevant questions largely ignored or barely explored to date involving the rather untapped potential of emerging and future ICT in terms of big data analytics and its application for catalysing and boosting the process of sustainable development towards achieving the long-term goals of sustainability, including the integration of its dimensions [20]. To put it differently, despite the proven role of the advanced forms of ICT in enhancing urban sustainability performance, the evolving approaches to smarter cities raise several issues, involve special conundrums, significant challenges, and pose potential risks to the environment—when it comes to their development and implementation in the context of sustainability [25]. It is highly important that future studies should go beyond only passing reference to the role of big data competing in addressing and overcoming the challenges of sustainability to emphasise and exploit the numerous opportunities available in this regard. However, for a detailed review of the field of smarter cities in terms of its materialisation, characterisation, research issues, challenges, and risks, the interested reader can be directed to Chapter 10 of a recent book published by Bibri [20]. Overall, most of the critical issues discussed earlier concerning smart cities of today as to their inadequate contribution to the goals of sustainable development and thus poor sustainability performance do apply to the emerging smarter cities, so do the tremendous potential for advancing sustainability. The latter has indeed become a topic of major importance in recent years, a mainstream theme in the debate on ICT innovation for sustainability in the context of smart cities of the future, as well as a key research direction and new wave of urban thinking, as adequately discussed above.

Smarter cities, which are characterised by the infiltration of computer and information intelligence into the operating and organising processes of urban life, are extremely well positioned to do a lot more in respect of sustainability. Besides, it is high time for smart cities in their transition to smarter cities to go beyond the technical advancement and industrial competitiveness that have prevailed for more than two decades or so to start focusing their efforts towards solving the urgent problems and pressing issues pertaining to sustainability and urbanisation. Especially, future ICT will pervade urban operations, functions, designs, strategies, services, and policies in the context of smarter cities, thereby being in strong position in instigating major transformations. This is anchored in the recognition that it offers fascinating possibilities for monitoring, understanding, analysing, probing, and planning smarter cities to strategically improve and maintain their contribution to the goal of sustainable development [20]. The underlying premise is that future ICT blends, and its application is founded on, data science, computer science, and complexity sciences in terms of designing, constructing, and planning smarter cities capable of tackling the kind of intractable and wicked problems associated with sustainability and bringing about drastic transformations (e.g., [18, 20]). In reference to smart cities of the future, Batty et al. [16] note that future ICT is said to unleash the kind of science that can be mobilised to instigate profound changes. Already, emerging ICT is being leveraged in accelerating environmental sustainability in both smart cities and sustainable cities (e.g., [5, 16, 21, 82, 112]), making it possible to approach a range of issues around environmental sustainability in cities from a whole new perspective. Further, it has been suggested that as ICT pervades urban environments, i.e., data sensing, data processing platforms, cloud and fog computing infrastructures, and wireless communication networks become more and more embedded throughout urban systems and domains as well as in citizens' objects, smart cities can become smarter as to improving sustainability and enhancing the quality of life of citizens (e.g., [16, 20, 106, 113, 124]).

All in all, smarter cities will open new windows of opportunity for drastic sustainable change, especially they are still at the early stage of their development, and thus could, if planned strategically and implemented purposefully, do a lot more to advance sustainability and enhance the quality of life of citizens, including the mitigation of environmental risks and digital divides posed by ICT itself. In particular, the big data computing paradigm that is driving the transition from smart cities to smarter cities is noticeably in a penetrative path across various urban systems and domains towards safely fuelling unhindered progress on many scales, and hence paving the way for catalysing and accelerating sustainable development. However, failing to exploit the disruptive and substantive effects of ICT of pervasive computing on sustainability in an increasingly computerised and urbanised world means that the battle for sustainability will be lost in the world's major cities [20].

Big data analytics and its application in smart and smarter cities

Research status and data growth projection

Having recently, as a research wave and direction, permeated and dominated academic circles and industries, coupled with its research status being consolidated as one of the most fertile areas of investigation beyond the realm of smart and smarter cities, big data analytics has attracted researchers, scholars, scientists, experts, and practitioners from diverse disciplines and professional fields—given its importance and relevance for generating well-informed decisions and deep insights of highly useful value to many sectors of society. Therefore, big data analytics is a rapidly expanding research area merging computer science, data science, and complexity sciences [16, 20], and becoming a ubiquitous term in understanding and solving complex challenges and problems in such fields as sustainable urban development, engineering, economics, education, healthcare, medicine, and telecommunication. The big data movement has been propelled by the intensive R&D activities taking place in academic and research institutions, as well as in industries and businesses—with huge expectations being placed on the upcoming innovations and advancements in the field. This includes the high influence big data analytics and its application will have on many facets of smart and smarter cities and their citizens (e.g., [5, 16, 18, 20, 54, 73, 79, 83, 104, 124]). Further to the point, however, a large part of ICT investment is being directed by giant technology companies, such as Google, IBM, Oracle, Microsoft, SAP, and CISCO, towards creating novel computing models and enhancing existing practices pertaining to the storage, processing, analysis, management, modelling, simulation, and evaluation of big data, as well as to the visualisation and deployment of the analytical outcome for different purposes [20]. Adding to this is the active, ongoing research within so many universities across the globe, especially in relation to smart and smart cities, for the purpose of enhancing the acquisition of data from multiple distributed sources, the management of data streams, the integration of heterogeneous data into coherent databases as well as the definition of observables to extract relevant information from available datasets, data transformation and preparation, methods for distributed data mining and network analytics, the organisation and composition of the extracted models and patterns as well as the evaluation of their quality, tools for visual analytics to study the behavioural patterns and models, methods for the simulation and prediction of the mined patterns and models, and so forth. Big data analytics is considered as a prerequisite technology for realising the novel applications and services offered and promised by the ICT visions of pervasive computing, which is a determinant enabler and powerful driver for such cities.

The deluge of urban data is, and will continue to be, unfolding and soaring, amounting to hundreds of exabytes every year, if not more than that, and covering so many aspects of urbanity in its complexity, breath, depth, and heterogeneity as manifested in, among others, the nature of urban systems and their continuous integration, that of urban domains and their coordination, and that of urban networks and their coupling This urban data growth will undoubtedly continue in this direction, and expectedly, the resulting datasets are set to proliferate and be coalesced, integrated, and coordinated. Generally, the digital data are projected to grow from 2.7 Zettabytes to 35 Zettabytes by the year 2020 [90, 146]. Manyika et al. [91] projects a growth of about 45% in the global data produced per year. It is estimated that more data are produced every 2 days at present than in all of history prior to 2003 [79, 117]. This explosive data growth is due to a number of the core enabling and driving technologies of ICT of various forms of pervasive computing, and their ever-growing embeddedness into the very fabric of modern and future cities.

Research issues and future prospects

The past few years have witnessed extensive investments in the ICT infrastructure of smart and smarter cities in terms of large-scale deployments across the globe, especially in big data analytics and its core enabling technologies. This is making it increasingly feasible to collect, store, manage, and analyse large amounts of data throughout urban domains and to deploy the analytical outcome to serve many purposes, despite the limited capacities of the prevailing analytic systems or data processing platforms in use. This new development is opening new windows of opportunity for invigorating the application demand for the urban sustainability solutions that big data analytics can offer. Concurrently, the application of big data analytics has been expanded beyond the realm of business intelligence (e.g., [33, 107]) in the wake of this development to include the field of smart and smarter cities in terms of their domains (e.g., [5, 16, 18, 20, 54, 79, 83, 108]). However, research on big data analytics and its application tends to deal largely with economic development (i.e., management, optimisation, effectiveness, innovation, productivity, etc.) and the quality of life in terms of service efficiency and betterment (e.g., [15, 41, 54, 73, 77, 108]) while overlooking and barely exploring the issues related to the different dimensions of sustainability. This paucity of research pertains particularly to the untapped potential of big data technologies and their novel applications for enhancing the environmental and social aspects of sustainability [20]. This in fact relates to the deficiencies of smart and smarter cities in this regard. As discussed above, such cities have, irrespective of which ICT visions they tend to instantiate in relation to their operational functioning, management, planning, and development, been subject to much debate, generating a growing level of criticism that essentially questions their added value to sustainability due to the lack of incorporating the fundamental goals of sustainable development, as well as falling short in considering the environmental and social indicators of sustainability (e.g., [2, 20, 25, 55, 82, 92]). Consequently, a recent research wave has started to focus on enhancing smart and smarter city approaches to achieve the required level of sustainability through alining urban operations, functions, designs, strategies, services, and policies with the goals of sustainable development using big data applications under what is labelled 'sustainable smart cities' (e.g., [5, 16, 18]).

Data sensing and processing, cloud and fog computing, and wireless networking technologies associated with big data analytics are being fast embedded into the very fabric of cities badging or regenerating themselves as smart and smarter to pave the way for utilising and applying the upcoming innovative solutions to overcome the challenges of sustainability and urbanisation in the years ahead. Also, the increasing convergence and advance of ICT is giving rise to new computationally augmented urban spaces that are both drastically changing living and working modes as well as enabling sophisticated operating and organising processes of urban life, which are quite different from what has been experienced hitherto on many scales. This is in response to the event of cities becoming more and more complex as systems and dynamically changing environments together with their domains getting more and more coordinated, their systems integrated, and their networks coupled. This concern those domains, systems, and networks that rely heavily on complex technologies to realise their full potential for responding to the challenges of sustainability and urbanisation or, possibly, addressing them from the source. All the above points well to new opportunities and alternative ways to develop, operate, probe, plan, and govern smart cities of the future or smarter cities.

The expansion and success of big data computing trend is increasingly stimulating smart and smarter city initiatives and projects as well as research opportunities to an increasing extent, especially in technologically and/or ecologically advanced nations. However there are significant challenges to address and overcome prior to achieving a more effective utilisation of big data analytics and related applications in the realm of smart and smarter cities, including technological, computational, organisational, social, cultural, and political. These are the object of the next section.

Urban data deluge

Datafication The big data revolution will transform the way we live, work, and think in the city. Datafication has become a buzzword in the era of big data. This buzzword describes an urban trend of defining the key to core city operations and functions through a reliance on big data computing and underpinning technologies. There is no official definition of datafication, at least in terms of it being in the dictionary. In the context of this paper, the notion of datafication denotes that cities today are dependent upon their data to operate properly—and even to function at all with regard to many domains of urban life, especially in relation to sustainable development [23]. It also refers to the collective tools, processes, and technologies used to transform a city to a data-driven enterprise. In all, datafication involves turning many aspects of urban life into computerized data and transforming this information into useful knowledge and valuable insights.

Datafication is also known as datafy. A city that implements datafication is said to be datafied. To datafy a city is to put it in a quantified format so it can be structured and analyzed. The so-called quantifiable information is what the data miners or data analysts look for and rely on different sources to find it. Cities are taking any possible quantifiable metric and squeezing useful knowledge out of it for enhanced decision-making and deep insights pertaining to many domains of urban life. Thus, they require data and extract knowledge to perform critical urban processes related to the operation and organization of urban life. Datafication entails that in a modern data-oriented urban landscape, a city's performance is contingent on having control over the storage, management, and analysis of the data as well as on the extracted knowledge in the form of applied intelligence. Datafying cities occurs through the data obtained from the sensors that are deployed across urban environments so that issues that can arise will be noticed and tackled before they become serious as related to diverse urban systems and domains in terms of operations, functions, services, designs, strategies, and policies. Tackling sustainability issues is one of the key concerns of the datafication of the city. With these sensors, cities can have, for example, a more detailed understanding of the various problems of environmental sustainability and can enact new policy regulations based on real-time data.

In recent years, there has been a marked intensification of datafication. This is manifested in a radical expansion in the volume, range, variety, and granularity of the data being generated about urban environments and citizens (e.g., [20, 23, 79, 81, 120]), with the aim of quantifying the whole of the city. We are currently experiencing the accelerated datafication of the city in a rapidly urbanizing world and witnessing the dawn of the big data era not out of the window, but in everyday life. Our urban everydayness is entangled with data sensing, data processing, and communication networking, and our wired world generates and analyzes overwhelming and incredible amounts of data. The modern city is turning into constellations of instruments and computers across many scales and morphing into a haze of software instructions, which are becoming essential to the operational functioning, planning, design, development, and governance of the city [23]. The datafication of spatiotemporal citywide events has become a salient factor for the practice of smart sustainable urbanism.

Urban data potentials and sources There has been much enthusiasm in the domain of smart sustainable/sustainable smart urbanism about the immense possibilities and fascinating opportunities created by the data deluge and its extensive sources with regard to improving urban operational functioning, management, planning, and design in line with the goals of sustainable development as a result of thinking about and understanding sustainability and urbanization and their relationships in a data-analytic fashion for the purpose of generating and applying knowledge-driven, fact-based, strategic decisions in relation to such urban domains as transport, traffic, mobility, energy, environment, education, healthcare, public safety, public services, governance, economy, and science and innovation [20]. The exponentially growing amount of the data being constantly produced across many urban domains, whether separated or coordinated, is at such a high value that it has become of astuteness and strategic value for urban planners, strategists, and policymakers in collaboration with ICT experts and data analysts to exploit, harness, and analyze these data for the purpose of increasing the contribution of smart and smarter cities to the goals of sustainable development [20]. Within such cities, citizens, activities, movements, processes, physical structures, urban infrastructure, distribution systems and networks, natural ecosystems, spatial organisations, scale stabilisations, socio-economic networks, facilities, services, spaces, and citizen objects all contribute to the generation of the huge amounts of data collected from heterogeneous and distributed sources. Basically, virtually every aspect of urbanity has become open to, and instrumented for, data collection, processing, and analysis. As a result, vast troves of information have become widely available on numerous aspects of urbanity, including social trends, global shifts, environmental dynamics, socio-economic needs, spatial and scalar patterns, land use patterns, travel and mobility patterns, traffic patterns, energy consumption patterns, life quality levels, and citizens' lifestyles and participation levels [20, 27]. The data from these sources and on these aspects cascade into urban data deluge, which calls for prudent big data applications that can churn out useful knowledge and valuable insights from this huge deluge. The sustainability of smart and smarter cities as well as the smartness of sustainable cities are being digitally fuelled and driven by the enormous data collected for analysis and deployment for enhanced decision-making purposes.

The evolving data deluge resulting from the increasing availability of the data being generated in continuous streams on daily basis (e.g., [15, 23, 79]) is pushing research on and the use of big data analytics to expand remarkably and its technologies to proliferate in urban domains on a massive scale. The rationale is that it is increasingly enriching and reshaping our experiences of how smart and smarter cities can evolve and further advance at many levels, thanks to its analytics which is indeed offering new opportunities for generating well-informed decisions and enhanced insights with respect to our knowledge of how fast and best to advance sustainability [20]. This is due to the analytical power of big data as a fundamental ingredient for the next wave of city analytics with regard to the useful knowledge that can be extracted and immediately applied to improve sustainability performance. The increased use of big data analytics as well as the profusion and proliferation of data are being driven by the emerging core enabling technologies: techniques, algorithms, devices, systems, infrastructures, platforms, and networks, as advances in ICT of pervasive computing, and their continuous embeddedness into a wide variety of urban practices, enabling more effective accessibility, production, and sharing of data more than ever (e.g., [79]). Important to note, though, big data are about the way they are exploited and their analytics is applied, as well as how new innovations are facilitated and diffused throughout the domains of smart and smarter cities through data themselves, especially in the context of sustainability and in connection with urbanisation [20].

City analytics City analytics entails the application of various techniques, algorithms, models, and processes based on the fundamental concepts of data science—i.e., data-analytic thinking and the principles of extracting useful knowledge from large masses of data for decision making [20]. Big data analytics techniques include, but are not limited to, data mining, machine learning, statistical analysis, and database querying, and whose application involves significant challenges due to the interdisciplinary and transdisciplinary character of urban data. Also, their use depends on the nature of the problem to be tackled or solved in relation to a given urban domain. Worth noting is that the process of data mining is the most applied technique in urban analytics within smart and smarter cities (e.g., [16, 20, 73]). The main difference between data mining and other techniques is that it focuses on the automated search for or extraction of useful knowledge from large masses of data (e.g., [107]). However, while this technique has recently become of focus in city analytics in relation to various domains of smart cities of the future (e.g., [16, 73, 79]) as well as to those of sustainable smart cities of the future [20, 27], much of the existing knowledge of urban sustainability has long been gleaned from studies characterised by data scarcity ('small data' studies) and involving the use of traditional data collection and analysis methods [20]. This form of academic and scientific research in the domain of sustainable urbanism has prevailed for three decades or so. This has consequently impacted the robustness of the obtained research results and hence the way sustainability as underpinned by theoretical perspectives and empirical investigations based predominately on such methods has been adopted as a set of practices in urban planning and development [20, 26]. Commonly, in the academic and scientific research within smart sustainable urbanism domain, 'small data' studies are associated with high cost, quick obsolescence, infrequent periodicity, incompleteness, inaccuracy, and inherent biases; moreover, they capture a relatively limited sample of data that are tightly focused, restricted in scope and scale, time and space specific, and relatively expensive to generate and analyse [16, 20, 79]. Therefore, there is a need for advanced or sophisticated approaches into data collection and analysis in the domain of smart sustainable urbanism that can provide additional depth and insight with respect to complex urban phenomena and dynamics. Accordingly, using big data techniques in city analytics holds great potential for transforming the knowledge of sustainable smart and smarter cities through the creation of a data deluge whose analysis can provide, as part of big data studies, much more sophisticated, more inclusive, finer-grained, wider-scope and -scale, realtime understanding and control of different aspects of urbanity in terms of its complexity and intricacy [20].

Core enabling technologies

Strands and permutations Like many domains or areas to which big data analytics can be applied, smart and smarter cities require the big data ecosystem and its components to be put in place as part of their ICT infrastructure prior to designing, developing, deploying, implementing, and maintaining the diverse applications that support sustainability through enhancing and optimising urban operational functioning, management, planning, and governance accordingly. As a scientific and technological area, the research strand concerned with the core enabling technological components underlying the big data ecosystem involves such sub-areas as low-level data collection and fusion, intermediate-level data processing, and high-level application action and service delivery, adding to cloud and fog computing models for hosting the associated devises, systems, and networks [20]. These are under vigorous investigation in both academic circles as well as the ICT industry towards the development of computationally augmented urban environments and spaces in smart and smarter cities as part of their informational landscape and as a result of the ICT visions of pervasive computing becoming deployable and achievable computing paradigms. In this respect, big data analytics as a prerequisite technology for realising such visions entails a number of permutations of the underlying core enabling technologies pertaining indeed to various forms of pervasive computing, and also shaped by the way these forms can be applied and integrated depending on the urban domain concerned and the scale, complexity, and extension of the smart and smarter city projects and initiatives to be developed and implemented. Regardless of the several possible ways in which a set or number of the core enabling technologies can be arranged, it is necessary, as suggested by Chourabi et al. [36], to take into account flexible design, quick deployment, extensible implementation, comprehensive interconnections, and advanced intelligence. However, while there are various permutations of the core enabling technologies that may well apply to most domains, there are some technical aspects and details that remain specific to the area of smart and smarter cities, more specifically, to the requirements, objectives, and resources of the smart and smarter city projects that are to be developed and implemented, which are usually determined by the nature, scale, and extension of the endeavor within a given context [27]. Most of, if not all, the possible permutations, though, involve sensing technologies and networks, data processing platforms, cloud computing and/or fog computing infrastructures, and wireless communication and networking technologies. These are intended to provide a full analytic system of big data and related functional applications based on advanced decision support systems and strategies and the underlying intelligence functions and simulation models that can be directed towards improving the contribution of smart and smarter cities to the goals of sustainable development and thus achieving the required level of sustainability. On this note, Batty et al. [16] state that much of the focus on smart cities of the future, 'will be in evolving new models of the city in its various sectors that pertain to new kinds of data and movements and actions that are largely operated over digital networks while at the same time, relating these to traditional movements and locational activity. Very clear conceptions of how these models might be used to inform planning at different scales and very different time periods are critical to this focus… Quite new forms of integrated and coordinated decision support systems will be forthcoming from research on smart cities of the future'.

A survey of related work Many reviews or surveys have, over the last few years, been carried out on big data analytics and its core enabling technologies. They tend to offer different perspectives on, or emphasise various dimensions of, the topic, while overlapping in many computational, analytical, and technological aspects [21, 27] pertaining to such components as techniques, algorithms, models, software tools, data processing platforms, and application forms, adding to related research issues and opportunities as well as challenges (e.g., [34, 35, 68, 69, 115, 125, 145]). Regarding the orientation of most of these surveys and other studies conducted thus far, they tend to focus on the business domain (e.g., [33, 54, 107]). This implies that the literature and thus research addressing big data analytics and its core enabling technologies in relation to the domain of sustainable urban development literature and thus research remains scant. In response to this paucity of literature and thus research on the core enabling technologies of big data analytics and its application in the context of sustainable smart cities, Bibri and Krogstie [27] provide a thorough survey on the topic by identifying and reviewing such technologies, in addition to synthesising and illustrating the key computational and analytical techniques, processes, and frameworks associated with the functioning and application of big data analytics. In doing so, the authors bring together research directed at a more conceptual, technical, and overarching level, a multi-perspectival approach which is intended to stimulate new research opportunities within the city domain, with a particular emphasis on the use of big data analytics and its core enabling technologies for advancing sustainability, as well as to add more depth and rigour to the existing studies in the field. The topics of the core enabling technologies of big data analytics addressed in rather more detail by the authors in their topical literature review include, but are not limited to, the following:

- Pervasive sensing for urban sustainability in terms of collecting and measuring urban big data; the IoT and related RFID tags; sensor-based urban reality mining; and sensor technologies, types, and areas in big data computing.
- Wireless communication network technologies and smart network infrastructures.
- Data processing platforms.
- Cloud and fog/edge computing in terms of characteristics, benefits, commonalities, and differences.
- Advanced techniques and algorithms.
- Privacy mechanisms and security measures.
- Conceptual and analytical frameworks with a focus on the process of data mining.

It might be useful to elaborate on, for instance, data processing platforms as one of the key technological components of the ICT infrastructure of smart and smarter cities. To begin with, while there exist many data processing platforms that can be used to perform big data analytics in terms of storage, manipulation, management, analysis, and evaluation of large masses of data, Hadoop MapReduce platform tends to be the most commonly applied one in the realm of smart cities (sse, e.g., [73, 108]) and sustainable smart cities [20, 21] due to the suitability of its functionalities as to handling urban data as well as to its benefits related to load balancing, flexibility, processing power, and cost effectiveness [21]. Additionally, it has become the primary data processing platform given its simplicity, scalability, and fine-grain fault tolerance [145]. It has various extensions, including Co-Hadoop, Hadoop++, HadoopDB, Cheetahand, and Dare. And numerous technologies (e.g., Apache PIG, Apache Hive, Apache Tez, Apache Giraph, Apache Cassandra, Apache Spark, Apache Scoop, Apache Zookeepe, Apache HBase, Apache Flume, and Scribe) can, together with HDFS, be built on the top of the Hadoop system to form a Hadoop ecosystem to enhance efficiency and functionality [20]. Several reviews of data processing platforms have been carried out from different perspectives, including conceptual, technological, computational, analytical, and general (e.g., [69, 115, 145]). However, Spark is considered one of the more efficient data processing platforms in terms of real-time data handling. Apache S4 platform is designed for processing continuous data streams in real time [103].

In addition, data processing platforms, standalone or as part of cloud computing or fog computing model, have the function of collecting, storing, coalescing, processing, managing, analysing, evaluating, and interpreting large masses of data in relation to a given urban system or domain/sub-domain to discover useful knowledge in the form of intelligence intended primarily to enhance decision-making processes by deploying the obtained analytical outcome or feeding it into decision support systems pertaining to urban operations, functions, services, strategies, and policies. Accordingly, the value of resulting intelligence lies in optimising the efficiency of infrastructures and facilities, integrating and coupling networks, reducing resource consumption, enhancing service delivery, streamlining planning and governance processes, and smarting up urban forms and physical structures. These occur through such functions as control, automation, optimisation, management, modelling, and simulation in the context of sustainability. However, merely keeping up with data flood coming from a single urban domain or sub-domain and storing the more relevant bits are daunting enough, not to mention effectively managing and analysing colossal datasets to spot hidden patterns and discover meaningful correlations. Nevertheless, massive efforts are being deployed to further advance the existing data processing platforms in the context of smart and smarter cities in response to the emerging wave of city analytics for which big data are the fundamental ingredients, to reiterate, and the underlying role in tackling and responding to the challenges of sustainable development and urban growth [20]. That is, this advancement is necessary for both enhancing the operational functioning and planning of urban systems as well as facilitating the coordination and coupling of urban domains in line with the vision of sustainability in the context of smart and smarter cities.

Further to the point, other topical studies tend to address varied technological components of big data while focusing on their use in relation to specific technologies, especially the IoT. For example, Ahmed et al. [1] explore the recent advances in big data analytics for the IoT systems as well as the key requirements for managing and analysing big data in an IoT environment. Bibri [21] reviews and synthesises the existing literature with the main objective of identifying and discussing the state-of-the-art big data applications enabled by the IoT and related sensor technologies, data processing platforms, and cloud and fog computing models in the context of sustainable smart cities of the future. In establishing an IoT-based smart city using big data analytics, Rathore et al. [108] describe their proposed system by its architecture and implementation prototype using Hadoop ecosystem and a wide variety of sensors for different purposes. This system entails data generation and collection, aggregation and integration, filtration, classification, preprocessing, computational analytics, and decision making.

Enabling capabilities Big data analytics as a set of advanced hardware technologies: devices, systems, platforms, architectures, and networks, constituting a key component of the ICT infrastructure of smart and smarter holds great potential to alter how such cities can be operated, managed, designed, and developed with regard to sustainability. This prospect has become clear as the underlying core enabling technologies will be, in the near future, the dominant mode of monitoring, understanding, analysing, and planning such cities to improve their contribution to the goals of sustainable development [16, 20]. Moreover, the broad availability of urban data is pushing research ever more into further advancing software technologies, including methods, techniques, algorithms, models, simulations, and protocols towards enhancing the efficiency of the extraction of useful knowledge pertaining to sustainability for the purpose of enhancing related urban intelligence functions and simulation models associated with energy, transport, mobility, healthcare, education, planning, and so on [27]. In reference to smart cities of the future and in relation to planning, Batty et al. [16] point out that sustainability issues will be dealt with using more effective models and simulations in city planning; in the era of big data, and this new technology will be a salient factor for planning forms of operation and organisation.

Big data applications and their sustainability effects and benefits

A critical evaluation of topical studies The intent here is to point out the differences between the notable topical studies carried out on big data applications that are particularly significant. Critically evaluating this research entails providing opinions as to what extent the findings or statement within this research are true, or to what extent they can be agreed with, as well as providing evidence taken from a range of sources which both agree with and contradict the presented arguments. With that in mind, significant opportunities exist for big data analytics and its application in relation to modernising and advancing smart and smarter cities as urban development models in terms of sustainability dimensions, among other things, as there is a broad range of urban domains and subdomains that can utilise big data technology as an advanced form of ICT in connection with sustainable development processes (e.g., [6, 16, 20, 21]). In other words, there exist numerous big data applications whose effects are compatible with the goals of sustainable development, as the knowledge resulting from the analysis of urban data in the form of applied intelligence usher in nearly all the domains of smart and smarter cities. This is due to the ubiquitous nature of ICT of pervasive computing and the associated extensiveness of data and the massive use of its analytics. However, while some topical studies address big data applications, they tend to deal largely with their use in relation to the efficiency of the proposed solutions, and there only are a few recent studies that focus on their use, yet only, in relation to some aspects of sustainability, or pass reference on the role of big data application in improving environmental sustainability.

A short review conducted by Al Nuaimi et al. [5] describes only a few big data applications in smart cities, namely power grid, traffic lights and signals, and eduction, and also explores the opportunities, benefits, and challenges of incorporating big data applications in smart cities. The authors conclude that while many opportunities are available for utilising big data technology in smart cities, there are still many issues that need to be addressed to achieve better application of this technology. Hashem et al. [54] describe a few big data applications in terms of efficiency and sustainability, including power grid, transport and traffic, healthcare, and governance, and also discuss the visions of big data analytics as to supporting smart cities by focusing on how big data can change urban populations at different levels. Another detailed survey of big data applications provided by Bibri [21] includes more urban domains than the above reviews, including transport, mobility, traffic, energy, power grid, environment, buildings, infrastructure, and large scale deployment, yet only in relation to environmental aspects of sustainability and in the context of the IoT as one ICT vision of pervasive computing. In investigating the potential contribution of smart city to environmentally sustainable urban development, Angelidou et al. [6] analyse comparatively a total of 32 smart city applications that can be found in the Intelligent Cities Open Source (ICOS) community repository. The authors classify the applications according to, among other criteria, the environmental issue they address, namely high traffic density, high amount of waste, increasing air pollution, increasing energy consumption/sinking resources, loss of biodiversity and natural habitat, and sinking water resources. However, they neither specify, or provide any detail on, which of these applications, and how they, relate to big data analytics. Kumar and Prakash [83] investigate the real potential of using big data analytics by decision makers and city planners in smart cities using a large number of case studies across the globe and hence including many undergoing pilot project for making cities smarter along with well-being benefits, yet with only a focus on power grids and traffic congestion. Focusing on social sustainability issues in terms of digital divides, Gebresselassie and Sanchez [51] ask, in their recent study on smart tools for socially sustainable transport, how smartphone applications (apps) can address social sustainability challenges in urban transport, if at all, with a particular focus on transport disadvantages experienced by citizens due to low income, physical disability, and language barriers and based on a review of 60 apps. This study reveals that transport apps have the potential to address or respond to the equity and inclusion challenges of social sustainability by employing universal design in general-use apps, including cost-conscious features and providing language options, as well as by specifically developing smartphone apps for persons with disabilities. However, while this is not to imply that such apps are a panacea for the equity and inclusion issues related to urban transport—but only one of the tools that can be used to address them, there nevertheless are other urban domains where new apps of similar use need to be developed and mainstreamed to address the same issues, including healthcare, education, and public and social services, and so on. Moreover, while this study brings the social aspects of sustainability to the forefront, and helps to gain a better understanding of the application of smart tools for socially sustainable transport, there is no mention of the role of big data analytics in the functioning of such apps, or how they relate to it at all, despite the mention of some articles that in fact address big data analytics and its application in smart cities in terms of the new smart applications proliferating urban transportation systems. Indeed, their operation must be based on big data on travel behaviour, mobility models, and multimodal transport. Furthermore, Bibri [20] provides a list of the other domains where big data can be applied to reach the required level of the different dimensions of sustainability, including dematerialisation and demobilisation, water management, natural ecosystem management, public safety and civic security, ecosystem service provision, urban design and land use, urban planning, and participatory governance.

Furthermore, big data applications can be categorised into two classes in the realm of smart and smarter cities: real-time applications and offline applications. As elucidated by Bibri [20, p. 491] regarding the former, 'the input is instantaneous or near real-time, analysis is fast, and system behaviour or application action is based on real-time mining…

for decision-making since all real-time applications require immediate responses. This implies that if decisions, …based on analytical results…, cannot be made within a specific time line, they simply become of no value or effect. Hence, it is crucial in this regard to provide the kind of data necessary for mining in a timely manner and to conduct the analysis…in a fast and sound fashion for accurate decision-making purposes. As to the latter, the input tends to be periodic and thus analysis occurs sporadically. System behaviour or application action comes in the form of delayed responses. For example, traffic control requires immediate responses to mange traffic in real-time; while environmental monitoring and management is associated with more delayed responses, as decisions are generally made over medium or long-term period'. Mohamed and Al-Jaroodi [98] provide an account of real-time and offline applications in the context of smart cities, with a focus on big data analytics.

All in all, in smart and smarter cities, big data analytics and its application are associated with such diverse intelligence functions as control, automation, optimisation, management, prediction, and enhancement, which are involved in the operational functioning and planning of urban systems as part of various urban domains. Hence, big data applications are well positioned to enhance the sustainability, efficiency, and resiliency performance of such cities, as well as the life quality, well-being, and equity of their citizens. Yet, the literature and thus research on the uses of big data analytics and its application in relation to sustainable development remains scant in the context of smart and smarter cities. This implies that, to reiterate, the potential of big data computing for advancing sustainability remains untapped and underexplored in the context thereof, and therefore needs to be fully exploited and investigated, respectively.

The key practical and analytical applications of big data technology for multiple urban domains Big data technologies and their applications are increasingly permeating the systems and domains of smart and smarter cities due to their potential for enabling their needed transition to sustainable development in an increasingly urbanised world. The range of the emerging big data applications as novel analytical and practical solutions that can be utilised for enhancing their sustainability performance is potentially huge, as many as the case situations where big data analytics may be of relevance to enhance some sort of decision or insight in connection with their domains or sub-domains. Bibri [23] identifies and enumerates the most common big data applications in relation to these domains or sub-domains, and also elucidates their sustainability effects associated with the underlying functionalities pertaining to the operations, functions, services, designs, strategies, and policies related to these domains or sub-domains, which specifically include the following:

- Transport and traffic.
- Mobility.
- Energy.
- Power grid.
- Environment.
- Buildings.
- Infrastructures.

- Urban planning.
- Urban design.
- Academic and scientific research.
- Governance.
- Healthcare.
- Education.
- Public safety.

For a detailed account of the big data applications associated with these domains or sub-domains, the interested reader can be directed to Bibri [23]. The reason for not including the rather long table containing these applications and their description in the form of a series of bullet points in this paper is that it would make it an unusually long paper. However, those applications are by no means, or intended to be, exhaustive. Also, they are synthesised and distilled from many studies conducted in more recent years, the most notable of which in order of priority in terms of their contribution to the synthesis and extracted essential meaning below are: Bibri [20, 21], Batty et al. [16], Angelidou et al. [6], and Al Nuaimi et al. [5], including the other works that are referenced (credited) in these studies. Of relevance to add, as to the technical processes, tools, and other details underpinning the functioning of big data applications, the interested reader can be directed to Bahga and Madisetti [11], one of the many books available out there on the topic, for a detailed account from a general perspective, and to Bibri [20] for an overview focusing mainly on sustainable smart and smarter cities.

Towards data-driven sustainable smart cities

Data-driven smart sustainable cities' is a term that has recently gained traction in academia, government, and industry to describe cities that are increasingly composed and monitored by ICT of ubiquitous and pervasive computing and thereby have the ability of using advanced technologies by city operations centers, planning and policy offices, research centers, innovation labs, and living labs for generating, processing, and analyzing the data deluge in order to enhance decision making processes and to develop and implement innovative solutions for improving sustainability, efficiency, resilience, equity, and the quality of life. It entails developing a citywide instrumented system (i.e., interagency control, planning, innovation, and research hubs) for creating and inventing the future. For example, a data-driven city operations centre, which is designed to monitor the city as a whole, pulls or brings together real-time data streams from many different agencies spread across various urban domains and analyze them for decision making and problem solving purposes related to urban operational functioning. As cities are routinely embedded with all kinds of ICT forms, including infrastructure, platforms, systems, devices, sensors and actuators, and networks, the volume of data generated about them is growing exponentially and diversifying, providing rich, heterogenous streams of information about urban environments and citizens. This data deluge enables the real-time analysis of different urban systems and interconnects data across different urban domains to provide detailed views of the relationships between different forms of data that can be utilized for advancing the various aspects of urbanity through new modes of operational functioning, planning, design, development, and governance in the context of sustainability, as well as provides the raw material for envisioning more sustainable, efficient, resilient, and livable cities [23].

We are moving into an era where instrumentation, datafication, and computation are routinely pervading the very fabric of smart or smarter cities, coupled with the interlinking, integration, and coordination of their systems and domains. As a result, vast troves of contextual and actionable data are being produced and used to operate, regulate, manage, and organize urban life. At the heart of this emerging era of data-driven urbanism is a computational understanding of urban systems and processes that reduces urban life to a set of logic, calculative, and algorithmic rules and procedures. Such understanding entails drawing together, interlinking, and analyzing urban big data to provide a more holistic and integrated view and synoptic intelligence of the city. This is being increasingly directed for improving, advancing, and maintaining the contribution of smart or smarter cities to the goals of sustainable development. In other words, the data-driven approach to urbanism has become the mode of production for sustainable smart cities, which are accordingly becoming knowable, tractable, and controllable in new dynamic ways, responsive to the data generated about them by reacting to the analytical outcome of many domains of urban life in terms of enhancing and optimizing operational functioning, planning, design, development, and governance in line with the goals of sustainable development. In a nutshell, a new era is presently unfolding wherein sustainable smart urbanism is increasingly becoming data driven. For supra-national states, national governments, and city officials, smart cities of the future or smarter cities offer the enticing potential of environmental and socio-economic development—more sustainable, livable, functional, safe, equitable, and transparent cities, and the renewal of urban centres as hubs of innovation and research (e.g., [5, 16, 20, 23, 84]).

The main scientific and intellectual challenges and common open issues

While there is a growing consensus among urban scholars and applied urban science experts that big data analytics and its application will be a determining or salient factor in the operational functioning, management, planning, design, and development of smart cities of the future or smarter cities, there still are significant scientific and intellectual challenges as well as open issues that need to be addressed and overcome for building such cities based on big data computing and underpinning technologies, and then for accomplishing the desired outcomes related to sustainability and urbanisation. Such challenges and issues pose interesting and complex research questions, and constitute fertile areas of investigation awaiting interdisciplinary and transdisciplinary teams of scholars, scientists, experts, and researchers working in the field of sustainable smart urbanism.

The rising demand for big data analytics and its core enabling technologies, coupled with the growing awareness of the associated potential to transform the way urban systems can be operated, managed, planned, and designed in the context of sustainability, comes with major challenges and open issues related to the design, engineering, development, implementation, and maintenance of data-centric applications in sustainable smart cities of the future or smarter cities. The challenges are mostly computational, analytical, and technical in nature, and sometimes logistic in terms of the detailed organisation and implementation of the complex technical operations involving the installation and deployment of the big data ecosystem and its components as part of the ICT infrastructure of such cities. They include, but are not limited to, the following, as compiled in Table 2.

There are many studies available (e.g., [5, 15, 16, 20, 66, 68, 78–81, 85, 124, 132, 133]) that provide a descriptive or analytical account of some of the above listed challenges (and also some of the open issues addressed below) as related to big data analytics and its applications and uses in smart and smarter cities. For example, Bibri [20] provides an overview of some of those challenges and potential ways to address and overcome them in the context of sustainable smart cities of the future, including data management, database integration across urban domains, urban growth and data growth, data sharing, data uncertainty and incompleteness, data accuracy and quality, and data governance.

Most of the challenges of big data analytics and its application arise from the nature of the data generated in smart and smarter cities in terms of their attributes in terms of (e.g., [16, 20, 23, 79, 86, 95, 96, 146]):

- Consisting of exabytes or terabytes of data;
- Being structured and unstructured in nature;
- Being often tagged with spatial and temporal labels; being commonly streamed from a large number and variety of sources;
- Being mostly generated automatically and routinely; being created in, or near, real-time;
- Being exhaustive in scope and scale by striving to capture entire populations or systems;
- Dramatically exceeding sample sizes commonly in use for small data studies;
- Being relational in database systems by containing common fields that enable the conjoining and combination of different datasets;
- Being fine-grained in resolution by aiming to be very detailed and uniquely indexical in identification; and holding the traits of extensionality (can add new fields easily), evolvability (can change dynamically), and scaleability (can expand in size rapidly).

Adding to the above primarily technological challenges are the financial, organisational, institutional, social, political, regulatory, and ethical ones, which are associated with the implementation, retention, and dissemination of big data across the domains of sustainable smart and smarter cities of the future [20]. In this regard, controversies over the benefits of big data analytics and its application involve limited access and related digital divides and other ethical concerns about accessibility [49]. For a detailed discussion of the challenges of urban big data and sustainable development, the reader can be directed to Kharrazi e al. [144]. Kitchin [79] provides a critical reflection on the implications of big data and smart urbanism, examining five emerging concerns, namely:

1. The politics of big urban data.
2. Technocratic governance and city development.

Table 2 Computational, analytical, technical, and logistic challenges. Source: Bibri [23]

Computational, analytical, technical, and logistic challenges
Design science and engineering constraints
Data processing and analysis
Data management in dynamic and volatile environments
Data sources and characteristics
Database integration across urban domains
Data sharing between city stakeholders
Data uncertainty and incompleteness
Data accuracy and veracity (quality)
Data protection and technical integration
Fault tolerance and scalability
Data governance
Urban growth and data growth
Cost and large-scale deployment
Evolving urban intelligence functions and related simulation models and optimization and prediction methods as part of exploring the notion of smart cities as innovation labs
Building and maintaining data-driven city operations centres or citywide instrumented system
Relating the urban infrastructure to its operational functioning and planning through control, automation, management, optimization, enhancement, and prediction
Creating technologies that ensure fairness, equity, inclusion, and participation
Balancing the efficiency of solutions and the quality of life against environmental and equity considerations
Privacy and security

3. Corporatisation of city governance and technological lock-ins.
4. Buggy, brittle and hackable cities.
5. The panoptic city.

Furthermore, to effectively and successfully use big data analytics for smart and smarter city applications, there are some open issues that need to be addressed and resolved, which mostly stem from the different challenges mentioned above. These issues are currently under investigation by the relevant industry and research communities. Regardless, no full solutions and robust approaches based on big data analytics can be offered in the context of such cities, and therefore, there is always room for improvements and innovations in the field of data-driven sustainable smart urbanism in terms of operational functioning, planning, design, and development. However, as regards he key open issues, there is, and will be, a growing need or increased demand for well qualified professionals and experts to design, develop, deploy, implement, operate, and maintain smart cities of the future or smarter cities with regard to their infrastructures, platforms, and applications. Specialised education and focused training in the field need to be strategically planned, carefully designed, and widely offered to obtain the needed human resources for fulfilling the purpose and meeting the expectations. In addition, it is necessary to set common assessment methods, measurements, and control policies for big data applications in such cities. Monitoring, controlling, and managing initiatives and implementations using advanced techniques and procedures is of crucial importance for ensuring the effectiveness, viability, quality, and durability of big data applications in the context of sustainability. Furthermore, as discussed previously in relation to smarter cities, political action is determining in the functioning, insertion, and evolution of sustainable smart cities of the future or smarter cities as an academic discourse which epitomises a socio-technical transition that is of significance to society. The political effects on smart and smarter cities play a pivotal role in how they will perform in terms of sustainability [20]. Also, the privilege of access to data by different city constituents with different political positions or powers must be taken into account and addressed carefully [5]. For a detailed account and discussion on the shaping role of political action in sustainable smart cities of the future, the interested reader can directed to Bibri and Krogstie [24]. In addition, it is important to investigate the side or harmful effects of technology use by citizens on their health and living, and hence to consider all the possible risks and unintended consequences in this regard.

Another open issue requiring special attention and careful consideration in the context of smart cities of the future or smarter cities is security and privacy concerns. When all systems become integrated, networked, and ubiquitous, data will be shared among all urban entities. It is a commonly held view that the more technologies monitor urban environments and collect information, the larger becomes the privacy threats, and the larger the networks, the higher the security risks (see [27] for a discussion of privacy mechanisms and security measures). Therefore, the ICT infrastructure and related data processing and cloud/fog computing platforms and infrastructures must be secured, privacy must be preserved, and information must be protected and thus not abused. Privacy—to selectively reveal oneself to the world—remains though the most critical issue in the context of the use of big data analytics and related applications in such cities. In fact, privacy is considered a basic human right in many democratic states, enshrined in national and supra-national laws in various ways, and related debates concern acceptable practices as to accessing and disclosing personal and sensitive information about a person [81]. Such sensitive information can relate to a number of a personal facets and domains creating a number of inter-related privacy forms, including [94, 110]:

- Identity privacy (to protect personal and confidential data);
- Bodily privacy (to protect the integrity of the physical person);
- Territorial privacy (to protect personal space, objects and property);
- Locational and movement privacy (to protect against the tracking of spatial behaviour);
- Communications privacy (to protect against the surveillance of conversations and correspondence); and,
- Transactions privacy (to protect against monitoring of queries/searches, purchases, and other exchanges).

These forms of privacy can be threatened and breached through a number of what are normally understood as unacceptable practices, each of which produces a different form of harm, as compiled by Kitchin [81] (Table 3) and detailed by Solove [118].

Data-driven smart sustainable/sustainable smart urbanism, urban science, data science, and big data computing and underpinning technologies create a number of potential privacy harms for several reasons. Kitchin [81] addresses five reasons, each of which raises significant challenges to existing approaches to protecting privacy (privacy laws and fair information practice principles), namely:

1. Datafication, dataveillance and geosurveillance.
2. Inferencing and predictive privacy harms.
3. Anonymization and re-identification.
4. Obfuscation and reduced control.
5. Notice and consent is an empty exercise or is absent.

There are clearly a number of ethical issues that arise from the development, deployment, and implementation of smart or smarter city technologies and accompanying urban science. The ethical dimensions of big data computing and underpinning technologies and urban science need to be seriously addressed and much more thoroughly mapped out. As widely acknowledged, many smart urban technologies capture data without the consent of citizens—who ought actually to have full details of what data are being generated, for what purpose these data are being used for, what kind of insights are being extracted from them or additional data inferred from them, how they are being captured, in addition to having shared control and benefit in how all data concerning them are subsequently used. This necessitates full consent together with full transparency with regard to the actions of those who control, process, and analyze data. Urbanism researchers and urban scientists need to consider the ethical implications of their work with respect to privacy harms and citizen permissions, and the purposes their research is intended for—even in the context of sustainability. As suggested by Kitchin [81], 'Beyond complying with relevant laws and institutional research board requirements, analysts have a duty of care to their fellow citizens not to expose them to harm through their analysis. Admittedly, what constitutes harm is often difficult to define and harms can occur directly or indirectly but nonetheless there is a need to consider how research might be used and to act responsibly. In addition, professional bodies should review their ethical standards in the light of big data and revise accordingly. City managers need to consider the potential pernicious effects of the roll-out of smart [urban] technologies and that notice and consent are all but impossible in many cases and take a pro-active role in brokering privacy and security arrangements on behalf of citizens through relevant contracting procedures and parameters. Here, all vendors would be compelled to comply with service level agreements concerning the operation of systems, what data are generated and how these can be used and shared, and be subject to privacy impact assessments.'

From a social perspective, new ethical frameworks based on gifting or sharing, in which citizens swap their data for a tangible return, offer an alternative underpinning for smart cities of the future or smarter cities and urban science. However, the 'gifting' remains compulsory with no alternatives and is also done without consent, and the benefits of 'sharing' data are most often stacked in favour of those capturing the data [81]. From a technical perspective, while there are several solutions and frameworks (especially modelling and simulations) that have recently been proposed (e.g., [77, 85]), the problem persists in the quest for unconventional security

Table 3 A taxonomy of privacy breaches and harms. Source: compiled by Kitchin [81] from Solove [118]

Domain	Privacy breach	Description
Information collection	Surveillance	Watching, listening to, or recording of an individual's activities
	Interrogation	Various forms of questioning or probing for information
Information processing	Aggregation	The combination of various pieces of data about a person
	Identification	Linking information to particular individuals
	Insecurity	Carelessness in protecting stored information from leaks and improper access
	Secondary use	Use of information collected for one purpose for a different purpose without the data subject's consent
	Exclusion	Failure to allow the data subject to know about the data that others have about her and participate in its handling and use, including being barred from being able to access and correct errors in that data
Information dissemination	Breach of confidentiality	Breaking a promise to keep a person's information confidential
	Disclosure	Revelation of information about a person that impacts the way others judge her character
	Exposure	Revealing another's nudity, grief, or bodily functions
	Increased accessibility	Amplifying the accessibility of information
	Blackmail	Threat to disclose personal information
	Appropriation	The use of the data subject's identity to serve the aims and interests of another
	Distortion	Dissemination of false or misleading information about individuals
Invasion	Intrusion	Invasive acts that disturb one's tranquillity or solitude
	Decisional interference	Incursion into the data subject's decisions regarding her private affairs

measures and privacy-enhancing mechanisms [20]. In this respect, several researchers (e.g., [132]) have recently provided clear directions for further empirical research and theory development about privacy concerns, in addition to sensitising techniques to identify the emergence, absence, or presence of privacy concerns among citizens. The same directions apply to security concerns. Regardless, the generation, accumulation, and processing of various data streams across urban domains are projected to continue to raise privacy and security issues, which is in fact, of concern to all the city constituents and stakeholders. Therefore, there is a need for novel measures and mechanisms that can ensure trustable data acquisition, transmission, and processing, not least to legitimate service provisioning associated with transport, traffic, mobility, accessibility, healthcare, utility, and public and social services, while ensuring citizens' privacy and guaranteeing services' integrity in the context of sustainability. Of importance to also consider is to develop smart cities of the future or smarter cities and urban science that have a set of ethical principles and values at their heart, which in fact is at the heart of social sustainability. The challenge is to acknowledge that there are a number of real ethical issues that need to be addressed and overcome, and to search for and find the kind of solutions (i.e., privacy-enhancing mechanisms and security measures) that also enable the sustainability benefits of big data computing and underpinning technologies to be realized. This is no easy task, but one that needs urgent redress, supported by viable, strategic pathways.

Addressing different kinds of challenges and open issues, Kitchin [80] provides a critical overview of data-driven urbanism, and critically examines a number of urban data issues, namely:

- Data ownership, data control, data coverage and access.
- Data security and data integrity.
- Data protection and privacy, dataveillance, and data uses such as social sorting and anticipatory governance.
- Technical data issues such as data quality, veracity of data models and data analytics, and data integration and interoperability.

Discussion, conclusion, and contribution

The principal aim of this paper was to provide a comprehensive, state-of-the-art review and synthesis of the field of smart and smarter cities as regards sustainability and related big data analytics and its application in terms of the underlying foundations and assumptions, research issues and debates, opportunities and benefits, technological developments, emerging trends, future practices, and challenges and open issues. These issues were addressed through dividing the paper into many sections and sub-sections where the relevant conceptual and theoretical subjects as well as thematic and topical categories were adequately elaborated on and thoroughly discussed from a variety of perspectives. This interdisciplinary and transdisciplinary review explored a broad array of the literature at the intersection of various disciplinary and scientific fields and technological areas. As such, it is meant to facilitate collaboration among these fields and areas for the primary purpose of generating the kind of interactional and unifiable knowledge that is necessary for a more integrated and deeper understanding of the topic of smart and smarter cities in relation to sustainability and related big data analytics and its application, as well as new insights and perspectives. The outcome of this extensive review allowed to establish the status of current knowledge about the sustainability of smart and smarter cities in their current state, as well as to highlight the potential of big data analytics and related novel applications for advancing their sustainability in the future.

First, the conceptual theoretical, and discursive constructs that make up this study, namely smart cities, smarter cities, and big data computing, were identified, described, examined, and discussed while emphasising the relevant issues and aspects relating to the cross-disciplinary integration underlying the multidisciplinary topic of this study. Worth noting, however, is that despite the prevalence of the concept and phenomenon of smart city worldwide, there still is obscurity facing its definition; nevertheless, there seems to be an agreement on what the smart or smarter city should achieve as to sustainability and urbanisation, and how advanced ICT (particularly big data analytics and its application) should be utilised to mitigate or solve the associated challenges and issues.

Second, a detailed, two-part survey of the relevant work in terms of issues, debates, gaps, benefits, opportunities, and prospects was provided. The focus of the first part on smart cities was on general and particular research areas, deficiencies, and potentials with regard to sustainability, and that on smarter cities was on characteristic features, social shaping dimensions, and the current issues of and future potentials for sustainability. The review indicates that smart and smarter cities in their current state involve several issues, pose special conundrums, and present significant challenges as to their development and implementation with regard to their contribution to sustainability. Accordingly, there are many critical questions that are worth investigating, which pertain to conceptual, theoretical, analytical, empirical, practical, social, and environmental aspects as related to sustainable development and the role of advanced ICT (especially big data applications) in achieving its goals. These aspects constitute new research avenues and thus opportunities which need to be pursued and realised, respectively, to advance the sustainability of smart cities of the future or smarter cities based on big data applications. This is anchored in the growing recognition that emerging and future ICT is extremely well positioned to make substantial contributions in this regard due to its disruptive, innovative, substantive, and transformational effects on forms of urban operations, functions, services, designs, strategies, and policies.

Third, big data analytics and its application in smart and smarter cities was addressed in terms of research status and data growth projection, the urban data deluge in city analytics and its sources and enabling capabilities, research issues and future prospects, core enabling technologies, and big data applications and their sustainability effects and benefits. With respect to the latter, a set of varied topics was dealt with, which included a critical evaluation of topical studies, analytical and practical applications for multiple smart/smarter city domains, and data-driven sustainable smart cities. The review reveals that tremendous opportunities are available for utilising big data applications in smart cities of the future or smarter cities to improve their contribution to the goals of sustainable development by optimising and enhancing urban operations, functions, services, designs, strategies, and policies, as well as by finding answers to challenging analytical questions and thereby advancing knowledge forms. The most common data-centric applications identified concerning urban domains: transport and traffic, mobility, energy, power grid, environment, buildings, infrastructures, urban planning, urban design, academic and scientific research, governance, healthcare, education, and public safety. The potential of big data technology lies in enabling smart cities of the future or smarter cities to harness and leverage their informational landscape in effectively understanding, monitoring, probing, and planning their systems and environments in ways that enable them to achieve the required level of sustainability. To put it differently, the use of big data analytics is projected to play a significant role in realising the key characteristic features of such cities in terms of sustainability, namely the efficiency of operations and functions, the efficient utilisation of natural resources, the intelligent management of infrastructures and facilities, the improvement of the quality of life and well-being of citizens, and the enhancement of mobility and accessibility. In all, the untapped potential of big data applications is evident and needs to be unlocked and exploited within such cities. In all, the untapped potential of big data applications is evident and needs to be unlocked and exploited within such cities. Already, many major cities have, whether within ecologically or technologically advanced nations, started to implement big data applications to reap their sustainability benefits [23].

Fourth, the key scientific and intellectual challenges were identified and the common open issues associated with the use of big data analytics and related applications in (enabling, operating, managing, and planning) smart and smarter cities were examined and discussed. Just as there are many new opportunities and benefits ahead to embrace and exploit, there are significant challenges and open issues ahead to address and overcome in relation to big data analytics to achieve a successful implementation of related novel applications in the context of smart cities of the future or smarter cities. These challenges are mostly of computational, analytical, technical, and logistic kinds. While most of these challenges and open issues are currently under investigation and scrutiny by the relevant research and industry communities, supported by technology and innovation policies, deploying big data applications in smart cities of the future or smarter cities requires overcoming other organisational, institutional, political, social, ethical, and regulatory challenges. These are likely to hinder the development and implementation of big data applications in such cities. Nevertheless, with all the success factors in place, coupled with a deep understanding of the emerging phenomenon of smart cities and an acknowledgement of the potential of big data computing, making such cities smarter in achieving sustainability becomes an attainable goal in an increasingly urbanised world. Important to add, while smart city and big data computing research is still in its infancy, the solutions to the involved challenges and issues can make it a very practical field. Worth noting moreover is that, as smarter cities are still emerging and in the early stage of their development, could, if planned strategically and linked to the agenda of sustainable development as part of related research, do a lot more for sustainability before they become widely adopted.

Concerning the value of this review and synthesis, the findings enable researchers and scholars to focus their work on the identified real-world challenges and open issues and the existing knowledge gaps pertaining to smart and smarter cities as urban development strategies in the context of technology and sustainability, respectively. Practitioners and experts can make use of these findings to identify common weaknesses and potential ways to solve them as part of the ongoing and future endeavours of sustainable smart urban development. In view of that, this interdisciplinary and transdisciplinary review provides a valuable reference for researchers and practitioners in related research communities and the necessary material to inform these communities of the latest developments in the field. It moreover serves to inform various city stakeholders about the yet unexploited benefits of big data applications with regard to sustainability.

As an emerging field of research, data-driven smart urbanism is remarkably heterogeneous with a diversity of research problems, integrating various theoretical and disciplinary perspectives. Accordingly, there are many avenues for future research, and here, I identify a few of them as deemed highly relevant to this paper. Considering what this paper intended to establish and highlight, one area of future research should focus on exploiting the upcoming innovations in big data computing and underpinning technologies for enhancing and advancing the practice of sustainable smart urbanism, in addition to finding more effective ways of addressing the extreme fragmentation of and weak connection between smart cities and sustainable cities as landscapes and strategies, respectively, on the basis of big data computing. This is practiced within the field of urban science. Of particular relevance also is to address the various issues associated with the current approaches to smart and smarter cities, namely shortcomings, inadequacies, deficiencies, and misunderstanding with respect to sustainability. This specifically pertains to the question of the need for such cities to incorporate, or increase their contribution to, the goals of sustainable development in their conceptualization and operationalization as part of future pathways towards achieving sustainable smart cities. Furthermore, an enticing area of research is the exploration of the available opportunities towards new approaches to sustainable smart urbanism. Indeed, sustainable smart cities as a leading paradigm of urbanism tends to take multiple forms of combining the strengths of smart cities and sustainable cities based on how the concept of sustainable smart cities can be conceptualized and operationalized.

Lastly, this paper provides a form of foundation for further discussion to debate over the disruptive, substantive, synergetic, and transformational effects of big data analytics and its application on forms of the operational functioning, management, planning, and development of smart and smarter cities in terms of sustainability practices in the future. Also, it presents a sort of basis for stimulating more in-depth research on smart and smarter cities and big data computing in the form of both qualitative analyses and quantitative investigations focused on establishing, uncovering, substantiating, and/or challenging the assumptions and claims underlying the relevance and meaningfulness of big data applications as technological advancements with regard to advancing sustainability. For example, owing to the disciplinary origins of ICT-oriented literature which resorts to what is labelled 'normative bias' of smart city research [135], and thus respective authors' literacy in advanced sophisticated technologies, there is a fertile area of research that may challenge the promises and claims that new discoveries in big data computing as futuristic advances in ICT hold for urban spaces at the expense of the basic consideration of factors that hamper or facilitate the implementation of big data applications. Indeed, attempts at dwelling at this intersection regarding technological advancements exist in the body of research on smart cities (e.g., [57, 89, 131, 136]). Nevertheless, much more needs to be done to fully exploit it and thus promote sustainable interdisciplinary and transdisciplinary smart and smarter city research (e.g., [20, 23, 135]).

Abbreviations

ICT: Information and Communication Technology; IoT: Internet of Things; ITU: International Telecommunication Union; UNECE: United Nations Economic Commission for Europe.

Authors' contributions

The author read and approved the final manuscript.

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2. Master of Science—research focused—in computer science with a major in Ambient Intelligence
3. Master of Science in computer science with a major in informatics
4. Master of Science in computer and systems sciences with a major in decision support and risk analysis
5. Master of Science in entrepreneurship and innovation with a major in new venture creation
6. Master of Science in strategic leadership toward sustainability
7. Master of Science in sustainable urban development
8. Master of Science in environmental science with a major in ecotechnology and sustainable development

9. Master of Social Science with a major in business administration (MBA)
10. Master of Arts in communication and media for social change
11. Postgraduate degree (one year of Master courses) in management and economics
12. PhD in computer science with a major in data-driven smart sustainable cities of the future

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Before embarking on his long academic journey, Bibri had served as an ICT and sustainability strategist, business engineer, researcher, project manager, and consultant. His current research interests include smart sustainable cities, urban science, sustainability science, data-intensive science, data-driven urbanism, as well as big data computing and its core enabling technologies, namely sensor technologies, data processing platforms, cloud and fog computing infrastructures, and wireless communication networks.

Bibri has authored four books whose titles are as follows:

1. The Human Face of Ambient Intelligence: Cognitive, Emotional, Affective, Behavioral and Conversational Aspects (525 pages), Springer, 07/2015.
2. The Shaping of Ambient Intelligence and the Internet of Things: Historico-epistemic, Socio-cultural, Politico-institutional and Eco-environmental Dimensions (301 pages), Springer, 11/2015.
3. Smart Sustainable Cities of the Future: The Untapped Potential of Big Data Analytics and Context-Aware Computing for Advancing Sustainability (660 pages), Springer, 03/2018.
4. Big Data Science and Analytics for Smart Sustainable Urbanism: Unprecedented Paradigmatic Shifts and Practical Advancements (500 pages).

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Paper 3

A Scholarly Backcasting Approach to a Novel Model for Smart Sustainable Cities of the Future: Strategic Problem orientation

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A scholarly backcasting approach to a novel model for smart sustainable cities of the future: strategic problem orientation

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Abstract

Sustainable cities have, since the early 1990s, been the leading global paradigm of urban planning and development thanks to the different models of sustainable urban form proposed as new frameworks for redesigning and restructuring urban places to achieve sustainability. Indeed, huge advances in some areas of sustainability knowledge and a multitude of exemplary practical initiatives have been realized, thereby raising the profile of sustainable cities worldwide. The change is still inspiring and the challenge continues to induce scholars and practitioners to enhance existing, and propose new, models. Especially, sustainable urban forms have been problematic, whether in theory or practice, so is yet knowing to what extent progress has been made towards sustainable cities. They are associated with a number of problems, issues, and challenges and thus much more needs to be done considering the very fragmented, conflicting picture that arises of change on the ground in the face of the expanding urbanization. This involves the question of how they should be monitored, understood, analyzed, planned, and even integrated so as to improve, advance, and maintain their contribution to sustainability. This brings us to the issue of sustainable cities and smart cities being extremely fragmented as landscapes and weakly connected as approaches, despite the proven role and untapped potential of advanced ICT, especially big data technology, for advancing sustainability under what is labeled 'smart sustainable cities.' Essentially, there are multiple visions of, and pathways to achieving, such cities, which depends on how they can be conceptualized. This paper details the two parts of strategic problem orientation by answering the guiding questions for Steps 1 and 2 of the futures study being conducted. This study aims to analyze, investigate, and develop a novel model for smart sustainable cities of the future using backcasting as a scholarly approach. It involves a series of papers of which this paper is the first one. We argue that a deeper understanding of the multi-faceted processes of change or the interplay between social, technological, and scientific solutions is required to achieve more sustainable cities. Visionary images of a long-term future can stimulate an accelerated movement towards achieving the long-term goals of sustainability. The proposed model is believed to be the first of its kind and thus has not been, to the best of one's knowledge, produced, nor is it being currently investigated, elsewhere.

Keywords: Smart sustainable cities, Sustainable cities, Smart cities, Compact cities, Eco-cities, Big data science and analytics, Sustainable development, Design principles and strategies, Planning practices, Backcasting, Futures study

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Introduction

Contemporary cities have a key role in strategic sustainable development; therefore, they have gained a central position in operationalizing this notion and applying this discourse. This is clearly reflected in the Sustainable Development Goal 11 (SGD 11) of the United Nations' 2030 Agenda, which entails making cities more sustainable, resilient, inclusive, and safe (United Nations 2015a). In this respect, the UN's 2030 Agenda regards information and communication technology (ICT) as a means to promote socio-economic development and protect the environment, increase resource efficiency, achieve human progress and knowledge in societies, upgrade legacy infrastructure, and retrofit industries based on sustainable design principles (United Nations 2015b). Hence, the multifaceted potential of the smart city approach as enabled by ICT has been under investigation by the United Nations (2015c) through their study on 'Big Data and the 2030 Agenda for Sustainable Development.' In particular, there is an urgent need for developing and applying data-driven innovative solutions and sophisticated approaches to overcome the challenges of sustainability and urbanization. Regardless, the world is drowning in data—and if policymakers and planners realize the potential of harnessing these data in collaboration with data scientists, computer scientists, and urban scientists, the outcome could solve major global problems. The underlying assumption is that the unfolding and soaring data deluge with its new and extensive sources hides in itself the answers to challenging analytical questions, enables the solutions to complex challenges, provides raw ingredients to build tomorrow's human engineered systems, and plays a key role in understanding urban constituents as data agents (Bibri 2019b).

New circumstances require new responses. This pertains to the spread of urbanization and the rise of ICT as important global shifts at play across the world today, and how they are drastically changing our understanding of sustainability in cities. The transformative force of urbanization and ICT, coupled with the central role that cities can play in advancing sustainability, has far-reaching implications for societies. By all indicators, the urban world will become largely technologized and computerized within just a few decades, and ICT as an enabling, integrative, and constitutive technology of the twenty-first century will accordingly be instrumental, if not determining, in addressing many of the conundrums posed, the issues raised, and the challenges presented by urbanization (Bibri 2019b). It is therefore of strategic value to start directing the use of emerging ICT into understanding and proactively mitigating the potential effects of urbanisation, with the primary aim of tackling the many wicked problems involved in urban planning, design, operational functioning, management, and governance, especially in relation to sustainability. This is another macro-shift at play across the world today. In fact, the rapid urbanization of the world pose significant and unprecedented challenges pertaining to sustainability (e.g., David 2017; Han et al. 2016; Estevez et al. 2016) due to the issues engendered by urban growth in terms of resource depletion, environmental degradation, intensive energy usage, air and water pollution, toxic waste disposal, endemic traffic congestion, ineffective decision-making processes, inefficient planning systems, ineffective management of urban infrastructures and facilities, poor housing and working conditions, public health and safety decrease, social vulnerability and inequality, and so on (Bibri 2019b). In short, the multidimensional effects of unsustainability in modern cities are most likely to exacerbate with urbanization. And urban growth will jeopardise the sustainability of cities (Neirotti et al. 2014).

Therefore, ICT has come to the fore and become of crucial importance for containing the effects of urbanization and facing the challenges of sustainability in the context of sustainable cities which are striving to improve, advance, and maintain their contribution to the goals of sustainable development. The use of advanced ICT in sustainable cities constitutes an effective approach to decoupling the health of the city and the quality of life of citizens from the energy and material consumption and concomitant environmental risks associated with urban operations, functions, services, designs, strategies, and policies. This pertains to the way such cities should be monitored, understood, analysed, and planned to improve, advance, and maintain their contribution to the goals of sustainable development using big data technology and its novel applications (Bibri 2019b). There is an increasing recognition that advanced ICT constitute a promising response to the challenges of sustainable development due to its tremendous, yet untapped, potential for tackling different socio–economic issues and environmental problems (see, e.g., Angelidou et al. 2017; Batty et al. 2012; Bibri and Krogstie 2016, 2017a; Kramers et al. 2014). Many urban development approaches emphasize the value and role of big data technologies and their novel applications as an advanced form of ICT in advancing sustainability (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bettencourt 2014; Bibri 2018a, b, 2019a, b, d, e; Bibri and Krogstie 2017b; Pantelis and Aija 2013; Sun and Du 2017).

Furthermore, at the beginning of a new decade, we have the opportunity to look forward and consider what we could achieve in the coming years in the era of big data revolution. Again, we have the chance to consider the desired future of data-driven smart sustainable cities. This will motivate many urban scholars, scientists, and practitioners to think about how the subject of 'data-driven smart sustainable cities' might develop, as well as inspire them into a quest for the immense opportunities and fascinating possibilities that can be created by the development and implementation of such cities. In this respect, we are in the midst of an expansion of time horizons in city planning. Sustainable cities look further into the future when forming scenarios and strategies to achieve them. The movement towards a long-term vision arises from three major mega trends or macro-shifts that shape our societies at a growing pace: sustainability, ICT, and urbanization. Recognizing a link between such trends, sustainable cities across the globe have adopted ambitious goals that extend far into the future and have developed different pathways to achieve them.

This paper details the two parts of strategic problem orientation by answering the guiding questions for Steps 1 and 2 of the futures study being conducted. This study aims to analyze, investigate, and develop a novel model for smart sustainable cities of the future using backcasting as a scholarly approach. It involves a series of papers of which this paper is the first one. We argue that a deeper understanding of the multi-faceted processes of change or the interplay between social, technological, and scientific solutions is required to achieve more sustainable cities.

The article unfolds as follows. In "The background of the futures study" section, the background of the futures study is provided. "A backcasting approach to strategic smart sustainable city planning and development" section outlines and discusses the research methodology being adopted in the futures study. "Strategic problem orientation" section details Steps 1 and 2 of the futures study. This paper ends, in "Discussion and conclusion" section, with a summary of the key findings and some reflections.

The background of the futures study

Sustainable development has, since its widespread diffusion in the early 1990s, significantly positively influenced urban planning and development. After reviving the discussion about the form of cities, it has undoubtedly inspired a whole generation of urban scholars and practitioners into a quest for the immense opportunities and fascinating possibilities that could be explored by, and the enormous benefits that could be realized from, the planning and development of sustainable urban forms. That is to say, forms for human settlements that will meet the required level of sustainability by reshaping the built environment in ways that can improve and maintain the contribution of cities to the goals of sustainable development in terms of reducing material use, lowering energy consumption, mitigating pollution, and minimizing waste, as well as in terms of improving equity, inclusion, the quality of life, and well-being (Bibri 2019b). During the 1990s, the discourse on sustainable development produced the notions of compact city and eco-city planning and development that became a hegemonic response to the challenges of sustainable development (Bibri and Krogstie 2017a, b; Jabareen 2006; Jenks and Dempsey 2005; Joss 2010, 2011).

Sustainable cities have been the leading global paradigm of urban planning and development (urbanism) (e.g., Jabareen 2006; Van Bueren et al. 2011; Wheeler and Beatley 2010; Whitehead 2003; Williams 2009) for more than three decades. Indeed, huge advances in some areas of sustainability knowledge and a multitude of exemplary practical initiatives have been realized, thereby raising the profile of sustainable cities. The subject of 'sustainable cities' remains endlessly fascinating and enticing, as there are numerous actors involved in the academic and practical aspects of the endeavor, including engineers and architects, green technologists, built and natural environment specialists, and environmental and social scientists, and, more recently, ICT experts, data scientists, and urban scientists (Bibri 2019b). However, sustainable urban forms have been problematic, whether in theory or practice, so is yet knowing to what extent progress has been made towards sustainable cities. Such forms are associated with a number of problems, issues, and challenges and thus much more needs to be done considering the very fragmented, conflicting picture that arises of change on the ground in the face of the expanding urbanization and the scarcity of resources. Current deficiencies, inadequacies, difficulties, fallacies, and uncertainties concern the planning, design, development, and governance of compact cities and eco-cities in the context of sustainability (e.g., Bibri and Krogstie 2017a, b; Dempsey and Jenks 2010; De Roo 2000; Jabareen 2006; Neuman 2005; Williams 2009). This involves the question of how sustainable urban forms should be monitored, understood, and analyzed so as to improve, advance, and maintain their contribution to sustainability. The underlying argument is that more innovative solutions and sophisticated approaches are needed to overcome the kind of wicked problems, unsettled issues, and complex challenges pertaining to sustainable urban forms in terms of their processes and practices. This bring us to the issue of sustainable cities and smart cities being extremely fragmented as landscapes and weakly connected as approaches (e.g., Angelidou et al. 2017; Bibri 2018a, 2019b; Bibri and Krogstie 2017a; Bifulco et al. 2016; Kramers et al. 2014), despite the proven role and the untapped potential of advanced ICT for advancing sustainability under what is labeled 'smart sustainable cities.' (e.g., Bibri 2018a, b; Bibri and Krogstie 2017b;

Kramers et al. 2014) In particular, tremendous opportunities are available for utilizing big data technologies and their novel applications in sustainable cities to improve, advance, and maintain their contribution to the goals of sustainable development.

In the meantime, smart cities are increasingly connecting the ICT infrastructure, the physical infrastructure, the social infrastructure, and the economic infrastructure to leverage their collective intelligence, thereby striving to render themselves more sustainable, efficient, functional, resilient, livable, and equitable. It follows that smart cities of the future seek to solve a fundamental conundrum of cities-ensure sustainable socio-economic development, equity, and enhanced quality of life at the same time as reducing costs and increasing resource efficiency and environment and infrastructure resilience. This is increasingly enabled by utilizing a fast-flowing torrent of urban data and the rapidly evolving data analytics technologies; algorithmic planning and governance; and responsive, networked urban systems. In particular, the generation of colossal amounts of urban data and the development of sophisticated data analytics for understanding, monitoring, probing, regulating, and planning the city are the most significant aspects of smart cities that are being embraced by sustainable cities to improve, advance, and maintain their contribution to the goals of sustainable development (e.g., Bibri 2018b, 2019b; Bibri and Krogstie 2017b, 2018). For supra–national states, national governments, and city officials, smart cities offer the enticing potential of environmental and socio–economic development, and the renewal of urban centers as hubs of innovation and research (e.g., Batty et al. 2012; Bibri 2019d; Kitchin 2014; Kourtit et al. 2012; Townsend 2013). While there are several main characteristics of smart cities as evidenced by industry and government literature (e.g., Hollands 2018; Kitchin 2014), the one that this futures study, and thus this paper, is concerned with is environmental, economic, and social sustainability. Indeed, there has recently been much enthusiasm in the domain of smart sustainable/sustainable smart urbanism about the immense possibilities and fascinating opportunities created by the data deluge and its extensive sources with regard to optimizing and enhancing existing urban practices and processes in line with the goals of sustainable development. This results from thinking about and understanding sustainability and urbanization and their relationships in a data–analytic fashion for the purpose of generating and applying knowledge–driven, fact–based, strategic decisions (Bibri and Krogstie 2018) in relation to such urban domains as transport, traffic, mobility, energy, environment, buildings, infrastructure, healthcare, public safety, design and planning, governance, and science. See Bibri (2019d) for a detailed list and descriptive account of big data applications for multiple urban systems and domains.

In light of the above, recent research endeavors have started to focus on smartening up sustainable cities through enhancing and optimizing their operational functioning, planning, design, development, and governance in line with the long-term vision of sustainability under what is labeled 'smart sustainable cities' (e.g., Bettencourt 2014; Bibri 2018a, b, Bibri 2019b; Bibri and Krogstie 2017a, b; Kramers et al. 2014; Shahrokni et al. 2015). This wave of research revolves particularly around amalgamating the landscapes of, and the approaches to, sustainable cities and smart cities in various ways in the hopes of reaching the required level of sustainability and improving the living standard of citizens (Bibri 2019b). It is generally concerned with addressing a large number and variety of issues related to sustainable cities and smart cities. Accordingly, numerous research opportunities are available and can be realized in the context of smart sustainable cities. Especially, this integrated approach tends to take several forms in terms of combining the strengths of sustainable cities and smart cities based on how the idea of smart sustainable cities can be conceptualized and operationalized. Indeed, several topical studies (e.g., Angelidou et al. 2017; Bibri 2018b, 2019b; Bibri and Krogstie 2017b; Kramers et al. 2014, 2016; Rivera et al. 2015; Shahrokni et al. 2015; Yigitcanlar and Lee 2013) have addressed the combination of the sustainable city and smart city approaches from a variety of perspectives. In addition, there is a host of opportunities yet to explore towards new approaches to smart sustainable urban planning and development to mitigate or overcome the extreme fragmentation of and weak connection between the landscapes and approaches of sustainable cities and smart cities, respectively. The focus in this futures study, and thus this paper, is on integrating the design concepts and planning practices of sustainable urban forms, namely compact cities and eco-cities, with big data technologies and their novel applications being offered by smart cities of the future, specifically data-driven cities.

Smart sustainable cities as an integrated and holistic approach to urbanism represent an instance of sustainable urban planning and development, a strategic approach to achieving the long-term goals of urban sustainability—with support of advanced technologies and their novel applications. Accordingly, achieving the status of smart sustainable cities epitomizes an instance of urban sustainability. This notion refers to a desired (normative) state in which a city strives to retain a balance of the socio-ecological systems through adopting and executing sustainable development strategies as a desired (normative) trajectory (Bibri and Krogstie 2019). This balance entails enhancing the physical, environmental, social, and economic systems of the city in line with sustainability over the long run-given their interdependence, synergy, and equal importance. This long-term strategic goal requires, as noted by Bibri (2018a, p. 601), 'fostering linkages between scientific research, technological innovations, institutional practices, and policy design and planning in relevance to sustainability. It also requires a long-term vision, a trans-disciplinary approach, and a system-oriented perspective on addressing environmental, economic, social, and physical issues.' All these requirements are at the core of backcasting as a scholarly approach to futures studies. This approach facilitates and contributes to the development, implementation, evaluation, and improvement of models for smart sustainable cities, with a particular focus on practical interventions for integrating and improving urban systems and coordinating and coupling urban domains using cutting-edge technologies in relevance to sustainability. One of the most appealing strands of research in the domain of smart sustainable urbanism is that which is concerned with futures studies. The relevance and rationale behind futures research approach is linked to the strategic planning and development associated with long-term sustainability endeavors, initiatives, or solutions. And backcasting is well suited to any multifaceted kind of planning and development process (e.g., Holmberg and Robèrt 2000), as well as to dealing with urban sustainability problems and challenges (e.g., Bibri 2019b; Carlsson-Kanyama et al. 2003; Dreborg 1996; Miola 2008; Phdungsilp 2011).

A backcasting approach to strategic smart sustainable city planning and development

As a special kind of scenario methodology, backcasting is applied here to build a future model for smart sustainable cities as a planning tool for facilitating urban sustainability. Backcasting scenarios are used to explore future uncertainties, create opportunities, build capabilities, and improve decision-making processes. Their primary aim is to discover alternative pathways through which a desirable future can be reached. Following Rotmans et al. (2000) taxonomy, scenarios can be classified into different categories, including projective and prospective scenarios, qualitative and quantitative scenarios, participatory and expert scenarios, and descriptive and normative scenarios. This futures study is concerned with a normative scenario, which takes values and interests (sustainability and big data technology) into account and involves reasoning from specific long-term goals that have to be achieved.

In general, the backcasting approach is applicable in futures studies dealing with the fundamental question of backcasting, which involves the kind of actions that must be taken to achieve a long-term goal. In this context, if we want to attain a smart sustainable city, what actions must be taken to get there? Here backcasting means to look at the current situation from a future perspective. As an analytical and deliberative process (Fig. 1), backcasting entails articulating an end vision and then developing a pathway to get from the present to that end point. In more detail, backcasting scenario is constructed from the distant future towards the present by defining a desirable future and then moving step-by-step backwards towards the present to identify the strategic steps that need to be taken to attain that specified future. This involves identifying the stumbling blocks on the way and the key stakeholders that should be involved to drive change, as well as developing and assessing the policy pathway in terms of planning practices and development strategies necessary to achieve the future outcome. The use of backcasting in futures studies assumes a vision of an evolutionary process of policy with a time frame of a generation or so, which is a basic principle to allow the policy actions to pursue the path towards, and potentially achieve, a sustainable future. Moreover, in urban sustainability, planning is about figuring out the 'next steps' which are quite literally the next concrete actions to undertake. Next steps are usually based on reacting to present circumstances, creativity, intuition, and common sense, but also (conceivably) are still aligned with the future vision and direction. Therefore, researchers in backcasting should not get obsessed with the next steps without considering how aligned they are with what they ultimately aim to achieve.

Figure 1 illustrates the backcasting process in which the future desired conditions are envisioned and steps are then defined to attain those conditions. In this regard,

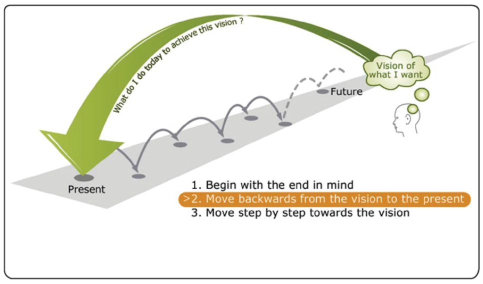

Fig. 1 The backcasting process from the Natural Step (source: Holmberg (1998))

envisioning the smart sustainable city as a future vision has a normative side: what future is desired? Backcasting this preferred vision has an analytical side: how can this desirable future be attained? Backcasting is about analyzing possible ways of attaining certain futures as well as their feasibility and potential (Quist et al. 2006). Specifically, in the quest for the answer to how to reach specified outcomes in the future, backcasting involves finding ways of linking goals that may lie far ahead in the future to a set of steps to be taken now and designed to achieve that end, and also facilitates discovery (Dreborg 1996).

Backcasting is viewed as a natural step in operationalising sustainable development (Holmberg and Robèrt 2000) within different societal spheres. In terms of its practical application, backcasting is increasingly used in futures studies in the fields related to sustainable urban planning as a formal element of future strategic initiatives. It is the most applied approach in futures studies when it comes to sustainability problems and the identification and exploration of their solutions. This involves a wide variety of areas, including strategic city planning (e.g., Phdungsilp 2011), sustainable city design (Carlsson-Kanyama et al. 2003). transportation and mobility (Banister et al. 2000), sustainable transportation systems (Akerman and Höjer 2006; Höjer 2000; Roth and Kaberger 2002), sustainable technologies and sustainable system innovation (Weaver et al. 2000), sustainable household (Green and Vergragt 2002; Quist et al. 2001), and sustainable transformation of organisations (Holmberg 1998). Backcasting studies must reflect solutions to a specified social problem in the broader sense (Dreborg 1996). Bibri (2018d) concludes that backcasting approach is found to be well-suited for long-term urban sustainability problems and solutions due to its normative, goal-oriented, and problem-solving character. Generally, as argued by Dreborg (1996), backcasting is particularly useful when:

- The problem to be studied is complex and there is a need for major change.
- The dominant trends are part of the problem.
- The problem to a great extent is a matter of externalities.
- The scope is wide enough and time horizon is long enough to leave considerable room for deliberate and different choices and directions of development.

Bibri (2018d) has recently conducted a comprehensive study on futures studies and related approaches. Its main focus is on backcasting as a scholarly approach to strategic smart sustainable city development. Its main objectives are to review the existing backcasting methodologies and to discuss the relevance of their use in terms of their steps and guiding questions for analyzing, investigating, and developing smart sustainable cities, as well as to synthesize a backcasting approach based on a number of notable future studies. Later, Bibri (2019b) adapted the approach, i.e., made minor changes so as to improve and clarify it in accordance with the overall aim of this futures study as well as the specificity of the proposed model. Indeed, a commonly held view is that the researchers' worldview and purpose remain the most important criteria for determining how futures studies can be developed and conducted in terms of the details concerning the questions guiding the steps involved in a particular backcasting approach. This helps to identify and implement strategic decisions associated with urban sustainability. However, the outcome of the adapted synthesized approach is illustrated in Table 1. Fundamentally, a backcasting study involves four steps (Höjer and Mattsson 2000), namely:

1. The setting of a few long-term targets.
2. The evaluation of each target against the current situation, prevailing trends, and expected developments.
3. The generation of images of the future that fulfill the targets.
4. The analysis of images of the future in terms of feasibility, potential, and path towards images of the future (Akerman and Höjer 2006).

The key assumptions of the applied backcasting approach encompasses the following:

- Efficient land use and conservation of green areas.
- Safeguarding biodiversity and ecosystem.
- Efficient utilization of resources.
- Decreasing resources usage and emissions.
- Integrating green and energy efficiency technologies.
- Mitigating environmental impacts (pollution and waste).
- Economic development and the quality of life.
- Social justice.
- Goal-oriented, design-oriented, and research-oriented.
- Policy-oriented and system-oriented.
- Time horizon of 25 years.
- Co-evolution of technology and society.

Strategic problem orientation

Part 1: On the futures study

This part of strategic problem orientation is concerned with setting up the direction of the model for smart sustainable cities of the future as a socio-technical system and an urbanism approach from the perspective of

Table 1 The guiding questions for each step in the backcasting study Source: Bibri (2019b)

Questions for backcasting steps	Methods
Step 1: Detail strategic problem orientation (Part 1) 1. What is the socio-technical system to be studied? 2. What are the aim, purpose, and objectives of the futures study in relation to this system? 3. What are the long-term targets declared by the goal-oriented backcasting approach? 4. What are the goals of sustainability these targets are translated to for scenario analysis?	Study design and problem formulation
Step 2: Detail strategic problem orientation (Part 2) 1. What are the key trends and expected developments related to the socio-technical system to be studied? 2. What are the major problems, issues, and challenges of sustainability and the underlying causes—the current situation? 3. How is the problem defined and what are the possible problem perceptions?	Trend analysis and problem analysis
Step 3: Generate a sustainable future vision 1. What are the demands (terms of reference) for the future vision? 2. How does the future sustainable socio-technical system and need fulfillment look like? 3. How is the future vision different from the existing socio-technical systems? 4. What is the rationale for developing the future vision? 5. Which sustainability problems, issues, and challenges have been solved or mitigated by meeting the stated objectives and thus achieving the specified targets and goals? 6. Which advanced technologies and their novel applications have been used in the future vision? 7. How can the future vision be made more sustainable and attractive?	Creativity method
Step 4: Conduct empirical research 1. What category of case studies is most relevant to the future vision? 2. How many case studies are to be conducted and what kind of phenomena do they intend to illuminate? 3. What is the rationale for the methodological approach adopted? 4. To what extent can this empirical research generate new ideas and serve to illustrate the theories underlying the future vision and to underpin its potential and practicality?	Case study method
Step 5: Specify and merge the components of the socio-technical system to be developed 1. What specific design concepts, planning practices, and technology elements are necessary? 2. What kind of urban centers and labs are necessary? 3. What spatial dimensions and scale stabilizations should be considered? 4. How can all of the ingredients be integrated into a model for strategic smart sustainable city planning and development?	Creativity method
Step 6: Perform backcasting backward-looking analysis 1. What urban and technological changes are necessary for achieving the future vision? 2. What structural, institutional, and regulatory changes are necessary? 3. How have the necessary changes been realized and what stakeholders are necessary? 4. What are the opportunities, potentials, benefits, and other effects of the future vision?	Backcasting analysis

integrating sustainability and technology and harnessing their clear synergy in advancing sustainability. Accordingly, we determine the aim, purpose, and objectives, as well as specify sustainability targets and goals. The long-term targets are to be translated into the goals of sustainability for scenario analysis.

Aim

This futures study aims to analyze, investigate, and develop a novel model for smart sustainable cities of the future using backcasting as a scholarly methodology. In doing so, it endeavors to integrate the physical landscape of sustainable cities with the informational landscape of smart cities as well as the two approaches to urban planning and development at the technical and policy levels in the context of sustainability. In more detail, it approaches this new integrated approach to urbanism from the perspective of combining the design concepts and planning practices of both the compact city and the eco-city, and then amalgamating the resulting outcome with the data-driven city in terms of the associated innovative solutions and sophisticated approaches pertaining to big data technologies and their novel applications for sustainability. Worth noting is that such approach, which is one among others that have been proposed in the field of smart sustainable cities and are being investigated further and hence not implemented yet, focuses on the core elements of urban sustainability, namely planning, design, and technology.

Purpose

As a research endeavor in its nature, this futures study intends to compile, transform, enhance, and disseminate knowledge of the smart sustainable city of the future. Its emphasis in this regard is on the untapped potential, unexploited benefits, unexplored opportunities, transformational effects, profound impacts, possible pathways, and future scenarios enabled by the emerging paradigm of big data science and analytics and the underpinning technologies with regard to sustainability. It also intends to, in general, develop the form of knowledge that can be used to guide sustainability transitions in an increasingly technologized, computerized, and urbanized world, as well as to, in particular, improve, advance, and maintain the contribution of sustainable cities to the goals of sustainable development with support of big data technologies and their novel applications as advanced forms of ICT. Worth noting is that the proposed model for smart sustainable cities is a result of the concept of urban sustainability as clarified, advocated, and established by many scholars, academics, and practitioners in the field, demonstrated in numerous real-world cities from across the globe, and, more importantly, evidenced by combining several cities from ecologically advanced nations in terms of planning practices and development strategies. According to several rankings, Sweden, Norway, Finland, Germany, and the Netherlands have the highest level of sustainable development practices (Dryzek 2005; Hofstad 2012).

Objectives

The objectives denote defining a set of specific actions for achieving the aim of the futures study. They include the following:

- Examining the planning practices and development strategies of both the compact city and eco-city to identify their preferred measures, as well as to determine the extent to which these measures produce the expected environmental, economic, and social benefits of sustainability.
- Integrating the most theoretically informed, practically successful, and widely adopted design concepts and planning practices of the compact city and the eco-city, predicated on the assumption that the former has a form and the latter is amorphous (formless).
- Compiling multiple pathways to achieving sustainable cities, and distilling the most important aspects of those being currently pursued to further inform the integration of the compact city and the eco-city based on the most advocated strategies of sustainable urban forms.
- Examining the up-to-date big data technologies and their novel applications pertaining to sustainability as associated with the data-driven city as an instance of smart cities of the future.
- Amalgamating the integrative model of the compact city and the eco-city with the data-driven city by connecting the eco-compact city in terms of policies, strategies, designs, spatial organizations, and scale stabilizations to its operational functioning and planning through control, automation, management, and optimization in the form of urban intelligence functions. This process requires digital instrumentation, urban operating system, cloud computing infrastructure, and big data ecosystem, as well as control rooms, management systems, and urban intelligence labs and centers (see Bibri 2019d for the anatomy of the data-driven smart sustainable city).

Sustainability targets and goals

Long-term targets

Here we identify the set of measures or indicators of the progress that is needed to get to the specified goals and thus realize the future vision or nearer to it in time. These measures include the following:

- High density and adequate diversity.
- Mixed land-use and social mix.
- Compactness.
- Sustainable transportation.
- Green and natural areas and biodiversity.
- Energy systems based on renewable resources, energy efficiency technologies, and integrated renewable solutions.
- Passive solar design and greening.
- Environmentally sound policies.
- Digital instrumentation, datafication, and computerization of the built environment based on cutting-edge big data technologies.
- Urban operations centers, strategic planning and policy offices, research centers, and innovation and living labs dedicated to advancing different areas of sustainability knowledge and its practice.

Specified goals

The model for smart sustainable cities of the future being predominantly based on the most prevailing, advocated, and successful models of sustainable urban form and supported with big data technologies and their novel applications as the most advanced solutions and approaches being offered by data-driven smart cities will ultimately result in numerous sustainability benefits, the most prominent among them are (e.g., Bibri 2019b; Bibri and Krogstie 2017b; Burton 2002; Dempsey 2010; Hofstad 2012; Jabareen 2006; Jenks and Dempsey 2005; Jenks and Jones 2010; Joss 2011; Joss, Cowley and Tomozeiu 2013; Rapoport and Vernay 2011):

- Decreased energy and material use.
- Reduced pollution.
- Minimized waste.
- Preserved open spaces and ecosystems.
- Reduced automobile use/car dependency.

- Effective mobility and accessibility.
- Enhanced quality of life and well-being.
- Improved equity and social justice.
- Community-oriented and livable human environments.
- Economic development and viability.

Part 2: (a) key prevailing trends and expected development

In this part of strategic problem orientation, the relevance of describing the broader context within which the analysis will take place lies in defining the different components that could act as direct inputs to the scenario analysis (Step 6).

Trend analysis: conceptual definition and analytical approach

The term 'trend' can be used to describe a pattern of change over time in some phenomena of importance and relevance to the observer. In the context of this paper, a trend comes in several forms, including global shifts, intellectual discourses, academic discourses, computing paradigms, scientific paradigms, and technological innovations. This paper is also concerned with the way these forms of trends intertwine with, affect, and inform one another in relevance to the phenomenon of smart sustainable cities.

The trend analysis as to the way it is meant to be conducted in this paper entails identifying the key forms of trends at play in the world today, and then performing an analysis to understand their nature, meaning, as well as their implications in relevance to the development of the novel model for smart sustainable cities of the future. In this case, the way forward is to look at a number of studies previously done on the diverse topics related to smart cities and sustainable cities to identify a set of pertinent, intertwined patterns of change of various kinds pertaining to these phenomena and their integration, and then to envision certain developments. One form of this envisioning in the context of this paper could be approached from the perspective on the synergy and complementarity of the respective forms of trends-of which the outcome is the development of multiple visions of smart sustainable cities as new approaches to urbanism, as well as how this phenomenon will evolve and the extent to which it will spread in the years ahead. This also involves other expected developments than smart sustainable cities and the continuation of this paradigm of urban planning and development in the future.

In addition, the trend analysis in this context requires probing what is causing the identified forms of trends to emerge, whether the causes will continue in that direction, what other external forces may affect the trends, whether they are part of rather larger societal shifts with far-reaching and long-term implications, and if there are some limitations and challenges associated with the trends.

Sustainable cities

Sustainable cities have been the leading global paradigm of urban planning and development (urbanism) (e.g., Jabareen 2006; Van Bueren et al. 2011; Wheeler and Beatley 2010; Whitehead 2003; Williams 2009) for more than three decades. In the early 1990s, the discourse on sustainable development produced the concept of sustainable cities that became a hegemonic response to the challenges of sustainability. In other words, the notion of sustainable development has been applied to, or adopted within, urban planning ever since to enable cities to move towards sustainability. In parallel, the research on and the development of sustainable cities (e.g., Girardet 2008; Williams 2009) have gained traction and prevalence worldwide, spanning a wide variety of urban domains in relation to the environmental, social, and economic dimensions of sustainability. In view of that, they have been supported and embraced by governments, policymakers, research institutions, universities, and industries (especially green and energy efficiency technologies) across the globe. The usefulness and relevance of the findings produced by the research in the field of urban sustainability and sustainable urban development has led sustainable cities as a drastic urban transformation to figure in many documents and agenda of policymakers of influential weight, such as the United Nations (UN), the European Union (EU), and the Organization for Economic Co-operation and Development (OECD). Also, such transformation has been provided as political statements and argumentations by many governments and organizations. In a nutshell, urban politics and policy around the world are infused with the language of sustainability. The whole point is that the subject of 'sustainable cities' remains endlessly fascinating and enticing, as there are numerous actors involved in the academic and practical aspects of the endeavor, including engineers and architects, green technologists, built and natural environment specialists, and environmental and social scientists, and, more recently, ICT experts, data scientists, and urban scientists (Bibri 2019b). All these actors are undertaking research and developing strategies to tackle the challenging elements of sustainable urbanism, adding to the work of policymakers and political decision-makers in terms of formulating and implementing regulatory policies and devising and applying political mechanisms and governance arrangements to promote and spur innovation and monitor and maintain progress in sustainable cities.

There are different instances of the sustainable city as an umbrella concept. These instances have been identified as models of sustainable urban forms, including compact city, eco-city, sustainable urbanism, green urbanism, new urbanism, and urban containment (Jabareen 2006). Of these, the compact city and the eco-city are advocated more sustainable and environmentally sound models. Following the advocacy and recommendation of several international policymakers, many state and local governments in varying contexts around the world have promoted both compact city and eco-city developments for what these models entail that is indispensable for sustainable urban futures (e.g., Bibri and Krogstie 2017b; Commission of European Communities 1990; Hofstad 2012; Jabareen 2006; Rapoport and Vernay 2011; van Bueren et al. 2011). However, according to Jabareen (2006), the compact city and the eco-city as the most prevalent models of sustainable urban form entail overlaps among them in their concepts, ideas, and visions: the compact city emphasizes density, compactness, diversity, and mixed-land use, whereas the eco-city focuses on renewable resources, passive solar design, ecological and cultural diversity, urban greening, and environmental management and other environmentally sound policies. In addition to land use patterns and design features, the compact city emphasizes sustainable transportation (e.g., transit-rich interconnected nodes), environmental and urban management systems (Handy 1996; Williams et al. 2000), energy-efficient buildings, closeness to local squares, more space for pedestrians, and green areas (Phdungsilp 2011). In view of that, using a thematic analysis approach, Jabareen (2006) ranks the compact city as more sustainable than the eco-city from a conceptual perspective: a matrix of sustainable urban forms for assessing the level of their sustainability performance based on the underlying topologies and design concepts.

Smart cities

In recent years, the smart city as a phenomenon has drawn increased attention and gained traction among universities, research institutes, governments, policymakers, businesses, industries, consultancies, and international organizations across the globe. The concept of the smart city became widespread during the mid 1990s due to the rise of ICT as a global shift. In recent years, it has become associated with urbanization as another global shift given the synergy between them, which are strongly at play across the world today. On this note, Townsend (2013) portrays urban growth and ICT development as a form of symbiosis. This entails an interaction that is of advantage to, or a mutually beneficial relationship between, both ICT and urbanization. One way of looking at this form of tie-in is that urbanization can open entirely new windows of opportunity, or simply provide a fertile environment, for cities to act as vibrant hubs of technological innovations in a bid to solve a wide variety of environmental, social, and economic problems and challenges, thereby containing the potential negative effects of urbanization. Further to the point, however, according to a recent review conducted by Bibri and Krogstie (2017a), the roots of the smart city concept date back to the 1960s under what is labeled the 'cybernetically planned cities', and then in urban planning and development proposals associated with networked or wired cities since the 1980s. In this respect, the common faces that emerged before, or in parallel with, the adoption of the concept of the smart city in urban planning and development around the mid 1990s include: networked cities, wired cities, cyber cities, digital cities, virtual cities, intelligent cities, knowledge cities, and cyber-physical cities, among other nomenclatures. For example, digital cities tend to focus on the hard infrastructure whereas intelligent cities on the way such infrastructure is used (Batty 1989, 1990, 1997). Moreover, several views claim that the concept of the smart city was introduced in 1994 (Dameri and Cocchia 2013), and that it is only until 2010 that the number of publications and scientific writings on the topic increased considerably, after the emergence of smart city projects as supported by the European Union (Jucevicius et al. 2014). As echoed by Neirotti et al. (2014), the smart city concept's origin can be traced back to the smart growth movement during the 1990s. Yet, it is not until recently that this movement led this concept to be adopted within urban planning and development (Batty et al. 2012).

In the early conceptualization of the concept, the smart city was mostly associated with the efficiency of technological solutions with respect to the operational functioning, management, and planning pertaining to energy, transport, physical infrastructure, distribution and communication networks, economic development, service delivery, and so forth. Smart growth implies the ability of achieving greater efficiencies through coordinating the forces that lead to policy-free growth: transportation, land use speculation, resource conservation, and economic development, rather than letting the market dictate the way cities grow (Batty et al. 2012). At present, however, many cities across the globe compete to be smart cities in the hopes of reaping the efficiency benefits economically, socially, or environmentally by taking advantage from the opportunities made possible by big data computing and its wider application across urban domains. It is also in this context that it has increasingly become attainable to achieve the required level of sustainability, resilience, equity, and the quality of life, in addition to ensuring higher levels of transparency and openness and hence democratic and participatory governance, citizenry participation, and social inclusion. Achieving all these benefits require sophisticated approaches, advanced technologies and their novel applications and services, resources, financial capabilities, regulatory policies, and strategic institutional frameworks, supported by an active involvement of citizens, institutions, and organizations as city constituents. Worth noting is that the growing interest in building smart cities based on big data technology is increasingly driven by the needs for addressing the challenges of sustainability and containing the effects of urbanization.

Smart sustainable cities

The concept of smart sustainable cities has emerged as a result of three important global shifts at play across the world, namely the rise of ICT, the diffusion of sustainability, and the spread of urbanization (e.g., Bibri 2018a, b, c, 2019b). As echoed by Höjer and Wangel (2015), the interlinked development of sustainability, urbanization, and ICT has recently converged under what is labelled 'smart sustainable cities.' Accordingly, smart sustainable cities are a new techno-urban phenomenon that materialized and became widespread around the mid-2010s (e.g., Ahvenniemi et al. 2017; Al-Nasrawi et al. 2015; Bibri 2018a, b; Bibri and Krogstie 2016, 2017a, c; Höjer and Wangel 2015; ITU 2014; Kramers et al. 2014; Kramers, Wangel and Höjer 2016; UNECE 2015b). As an integrated framework and holistic urban development approach, they amalgamate the strengths of sustainable cities in terms of the design concepts and planning practices of sustainable urban forms and those of smart cities in terms of the innovative solutions and sophisticated approaches primarily developed for sustainability and mainly offered by big data technology (Bibri 2018a, 2019b; Bibri and Krogstie 2017b, c). The whole idea revolves around leveraging the convergence, ubiquity, advance, and potential of ICT of pervasive computing and its prerequisite enabling technologies, especially big data analytics, in the transition towards the needed sustainable development and sustainability advancement in an increasingly urbanized world. Therefore, smart sustainable cities are increasingly gaining traction and prevalence worldwide as a response to the imminent challenges of sustainability and urbanization. They are moreover being embraced as an academic pursuit, societal strategy, and, thus, evolving into a scholarly and realist enterprise around the world, not least within ecologically advanced nations. In a nutshell, the concept and development of smart sustainable cities are gaining increased attention worldwide among research institutes, universities, governments, policymakers, and ICT companies.

Given the general consensus about the benefits of smart sustainable cities, coupled with the relevance and usefulness of the findings produced thus far in the field, the related research and development has been supported and advocated by the United Nations (UN), the European Union (UN), and the Organization for Economic Cooperation and Development (OECD), and other international organization and policy bodies (Bibri 2019b). Also, many city governments in ecologically advanced nations have recently set ambitious targets to smarten up their sustainable cities using a variety of initiatives and programs. Or, they have adopted the concept of smart sustainable cities by implementing big data applications to reach the required level of sustainability. Accordingly, it has become of crucial importance to develop and utilize new methods for measuring the smart performance of urban sustainability (e.g., Al-Nasrawi et al. 2015).

Big data science and analytics

We are living at the dawn of what has been termed as 'the fourth paradigm of science,' a scientific revolution that is marked by the recent emergence of big data science and analytics as well as the increasing adoption and use of the underlying technologies (large-scale compute, data-intensive techniques and algorithms, and advanced mathematical models) in scientific and scholarly research practices. Everything about science development and knowledge production is fundamentally changing thanks to the unfolding and soaring data deluge. Data-intensive science is a data-driven, exploration-centered form of science, where big data computing and the underpinning technologies are heavily used to help scientists and scholars manage, analyze, and share data for multiple purposes (Bibri 2019b). Data-intensive science as a paradigm and epistemological shift involves mainly two positions. The first position is a form of inductive empiricism in which the data deluge, through analytics as manifested in the data being wrangled through an array of multitudinous algorithms to discover the most salient factors concerning complex phenomena, can speak for itself free of human framing and subjectivism, and without being guided by theory (as based on conceptual foundations, prior empirical findings, and scientific literature). As argued by Anderson (2008), 'the data deluge makes the scientific method obsolete' and that within big data studies 'correlation supersedes causation, and science can advance even without coherent models, unified theories, or really any mechanistic explanation at all.' This relates to exploratory data analysis, which may not have pre-specified hypotheses, unlike confirmatory data analysis used in the traditional way of doing science that does have such hypotheses. The second position is data-driven science, which seeks to generate hypotheses out of the data rather than out of the theory, thereby seeking to hold to the tenets of the scientific method and knowledge-driven science (Kelling et al. 2009, p. 613). Here, the conventional deductive approach can still be employed to test the validity of potential hypotheses but on the basis of guided knowledge discovery techniques that can be used to mine the data to identify such hypotheses. It is argued that data-driven science will become the new dominant mode of scientific method in the upcoming Exabyte/Zettabyte Age because its epistemology is suited to exploring and extracting useful knowledge and valuable insights from enormous, relational datasets of high potential to generate more holistic and extensive models and theories of entire complex systems rather than parts of them, an aspect which traditional knowledge-driven science has failed to achieve (Kelling et al. 2009; Miller 2010).

In light of the above, the upcoming data avalanche is thus the primary fuel of this new age, which powerful computational processes or analytics algorithms are using to generate useful knowledge for enhanced decision-making and deep insights pertaining to a wide variety of practical uses and applications (e.g., developing more sustainable, efficient, resilient, livable, and equitable cities). The scope and impact of big data science and analytics will continue to expand enormously in the upcoming decades as scientific data and data about all branches of science become overwhelmingly abundant and ubiquitously available (Donoho 2015). Especially, significant progress has been made within data science, information science, computer science, and complexity science with respect to handling and extracting knowledge and insights from large masses of data, and these have been utilized within urban science (e.g., Batty et al. 2012; Bibri 2019a, b; Bibri and Krogstie 2017c; Kitchin 2014, 2016).

Big data computing is an emerging paradigm of data science, a typical model that is of multidimensional data mining for scientific discovery over large-scale infrastructure. It employs sophisticated computational methods to automatically extract useful knowledge and valuable insights from large masses of data—huge in volume, high in velocity, created in near or real-time, diverse in variety, exhaustive in scope, fine-grained in resolution, relational in structure, and extensible and scaleable in nature—using data science methods, processes, and systems. It has emerged as a result of the rise, advance, and prevalence of ICT as a global shift, as well as of the maturity and evolvement of the dominant ICT visions of ubiquitous computing into achievable and deployable computing paradigms, especially the IoT. However, it is not until recently that big data computing came to the fore and became of importance and relevance as a research area within smart sustainable urban planning and development (see, e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bettencourt 2014; Bibri 2018a, b, 2019a, b; Bibri and Krogstie 2016, 2017b; Khan et al. 2015; Kumar and Prakash 2014). The multifaceted potential of the smart city approach has been under investigation by the United Nations (2015c) through their study on 'Big Data and the 2030 Agenda for Sustainable Development,' to reiterate. On the whole, big data computing paradigm is clearly on a penetrative path across all the systems and domains of smart sustainable cities that rely on sophisticated technologies in their operational functioning, management, planning, development, and governance. In general, big data are regarded as the most scalable and synergic asset and resource for modern cities to enhance their performance on many scales. Unsurprisingly, there is a strong organizational, institutional, and governmental support for and commitment to big data technology-industry associations and consortia, business communities, scholarly and scientific research communities, policy bodies, and governmental agencies due to its tremendous (yet untapped) potentials and rapidly expanding success in relation to academic research and social practice.

As a new area of science and technology, 'big data science and analytics embodies an unprecedentedly transformative power—which is manifested not only in the form of revolutionizing science and transforming knowledge, but also in advancing social practices, catalyzing major shifts, and fostering societal transitions. Of particular relevance, it is instigating a massive change in the way both sustainable cities and smart cities are understood, studied, planned, operated, and managed to improve and maintain sustainability in the face of expanding urbanization' (Bibri 2019c, p. 79). To put it differently, these urban practices are becoming highly responsive to a form of data-driven urbanism that is the key mode of production for what have widely been termed smart sustainable cities whose monitoring, understanding, and analysis are increasingly relying on big data technologies.

In recent years, there has been a marked intensification of datafication. This is manifested in a radical expansion in the volume, range, variety, and granularity of the data being generated about urban environments and citizens (e.g., Kitchin 2014, 2015, 2016), with the primary aim of quantifying the whole of the city, putting it in a data format so it can be organized and analyzed. We are currently experiencing the accelerated datafication of the city in a rapidly urbanizing world and witnessing the dawn of the big data era not out of the window, but in everyday life. Our urban everydayness is entangled with data sensing, data processing, and communication networking, and our wired world generates and analyzes overwhelming and incredible amounts of data. The modern city is turning into constellations of instruments and computers across many scales and morphing into a haze of software instructions, which are becoming essential to the operational functioning, planning, design, development, and governance of the city. The datafication of spatiotemporal citywide events has become a salient factor for the practice of smart sustainable urbanism.

As a consequence of datafication, a new era is presently unfolding wherein smart sustainable urbanism is increasingly becoming data-driven. At the heart of such urbanism is a computational understanding of urban systems and processes that renders urban life a form of logical rules and algorithmic procedures—which is underpinned and informed by data-intensive-scientific approaches to urban science and urban sustainability, while also harnessing urban big data to provide a more holistic and integrated view and synoptic intelligence of the city (Bibri 2019b). This is increasingly directed towards improving, advancing, and maintaining the contribution of sustainable cities to the goals of sustainable development in an increasingly urbanized world. This relates to what has been dubbed data-driven smart sustainable urbanism (Bibri 2019b).

In a nutshell, the Fourth Scientific Revolution is set to erupt in cities, break out suddenly and dramatically, throughout the world. This is manifested in bits meeting bricks on a vast scale as instrumentation, datafication, and computerization are permeating the spaces we live in. The outcome will impact most aspects of urban life, raising questions and issues of urgent concern, especially those related to sustainability and urbanization. This pertains to what dimensions of cities will be most affected; how urban planning, design, development, and governance should change and evolve; and, most importantly, how cities can embrace and prepare for looming technological disruptions and opportunities.

The key external forces affecting the integration of the trends: the role of political action in smart sustainable cities

Smart sustainable cities are the product of socio-culturally-conditioned frameworks. This includes how and why the underlying data-driven processes and practices have emerged and become disseminated at the urban level and hence discursively constructed and materially produced through diverse socio-political institutions and organizations. In this respect, it is important to recognize the interplay between smart sustainable cities as a form of sustainability transition and other societal scales, as well as the links to political processes on a macro level, i.e., regulatory policies and governance arrangements. This relates to the dialectic relationship between societal structures and smart sustainable cities in the sense of each affecting and being affected by the other (see Bibri and Krogstie 2016 for a detailed discussion). The focus here is rather on how the former affects the latter, which is one of the objectives of the trend analysis. This one way relationship has been approached from a variety of perspectives, including transition governance, innovation system, and discourse analysis. From a transition governance perspective, government is one of the key actors involved in any form of sustainability transition through various governance arrangements, including funding schemes, research management (regulation of public research institutes), innovation and technology policies, regulatory standards, market manipulations, public–private collaborations and partnerships, and so on (e.g., Bibri 2015). In this respect, the government generates top–down pressure from regulation and policy and the use of market and other forms of incentives, while promoting, spurring, and stimulating the collective learning mechanisms by supporting innovation financially and providing access to the needed knowledge (Rotmans et al. 2001). Further, recommendations for smart sustainable cities as a major urban transformation, which entails a set of intertwined socio-technical systems and a cluster of interrelated discourses embedded in the wider socio-technical landscape, are unlikely to proceed without parallel political action (Bibri and Krogstie 2016). In general, drastic shifts to sustainable (and) technological regimes 'entail concomitantly radical changes to the socio-technical landscape of politics, institutions, the economy, and social values' (Smith 2003, p. 131).

Furthermore, political action is of influence in the context of smart sustainable cities as both a techno-urban discourse and an amalgam of innovation systems (Bibri and Krogstie 2016). Indeed, it is at the core of discourse theory (e.g., Foucault 1972) in terms of the material mechanisms and practices that can be used to translate urban visions into concrete strategies and projects and their institutionalization in urban structures (Bibri 2018a). Likewise, it is at the heart of the theoretical models of innovation system (e.g., Chaminade and Edquist 2010; Kemp 1997; Kemp and Rotmans 2005; Rånge and Sandberg 2015). Political processes represent the set-up under which dynamic networks of urban actors can interact within diverse industrial sectors in the development, diffusion, and utilization of knowledge and technology pertaining to smart sustainable urban planning and development.

Concerning the macro processes of regulation as one of the key components of political action, the act of regulating entails a set of principles, rules, or laws designed to govern urban behavior in terms of planning and development by carrying out legislations. Regulating city planning and development through policies is the responsibility of many different government departments and agencies. In other words, regulations are issued and enforced by various regulatory bodies formed or mandated by city governments to carry out the provision or intent of legislations. A city government affects urban planning and development through regulatory policies as a way to promote sustainability efforts. Most city governments have some regulations covering a variety of urban areas, including transport, traffic, mobility, natural environment, built infrastructure, green infrastructure, energy, land use, health, education, safety, as well as science and innovation in the context of sustainability.

On the whole, political action is of critical importance to, if not determining in, the emergence, insertion, functioning, and evolution of smart sustainable cities as an academic discourse, or rather to the construction, dissemination, and establishment of smart sustainable urban planning and development as an intellectual discourse. Related urban transformations have a quite strong governmental and policy support within ecologically advanced nations. The main argument is that smart sustainable cities—as an instance of sustainable urban development approach-are not an element closed in the 'ivory tower' of the research and industry communities, but they are influenced by the macro-political practices in connection with sustainable development and ICT innovation (Bibri 2018a). Such cities figure in many policy documents and agenda as well as political statements and argumentations, in addition to being used by many institutions and organizations of influential weight at the national and international levels, to reiterate. All in all, as a corollary of its dynamic interaction with academic and intellectual discourses, politics forces their emergence, insertion, functioning, and evolution (Foucault 1972). Bibri and Krogstie (2016) provide an account of some of the common political mechanisms used in this process, which represent facets of the operations that link smart sustainable cities and political action, including the following:

- Creating regulatory and policy instrument and incentives and carrying out legislations.
- Assigning scholarly roles and institutional positions to particular institutions and organizations, thereby authorizing them and legitimizing their actions as to R&D activities, technology and innovation policy formation, constructing and implementing new visions, and so on.
- Government involvement in projects and initiatives through funneling investments, providing positive incentives, advocating product and service adoption, organizing forums and symposiums, encouraging national and local programs, and devising comprehensive plans.
- Accumulating and preserving the relevant body of knowledge as well as disseminating and teaching concepts, visions, and principles, which is typically carried out inside research and innovation centers and higher educational institutions.

Furthermore, macro processes of political regulation are also of particular relevance to backcasting as a form of strategic urban planning and development related to sustainability and its advancement based on ICT as part of larger societal shifts. To move cities toward sustainability by improving their contribution to the goals of sustainable development using the innovative solutions and sophisticated approaches being offered by big data technology, policy actions should be, according to Bibri (2018a, p. 547), fostered through relevant principles and values, and the environmental, social, and economic impacts associated with sustainability need to be anticipated and assessed. As a normative scenario, backcasting in turn is a suitable and useful framework for supporting policymakers and facilitating their actions to guide sustainability transitions. The choice of such framework to develop scenarios of smart sustainable cities is supported and justified by its appropriateness to reach the policy targets (e.g., sustainable development goals) in tandem with societal development. In addition, backcasting scenarios may be capable of generating new policy directions needed if cities are to become smart sustainable (see OECD 2002 for guidelines towards environmentally sustainable transportation). Furthermore, the use of backcasting methodologies in futures studies assumes a vision of an evolutionary process of policy with a time frame of a generation or so, which is a basic principle to allow the policy actions to pursue the path towards, and potentially achieve, smart sustainable cities as a form of sustainability transition. The backcast of an alternative future is intended to reveal the relative implications of different policy actions and related targets and goals (Robinson 1982).

(b) The current situation

Sustainable cities—compact city and eco-city models of sustainable urban form

Deficiences, limitations, difficulties, fallacies. uncertainties, opportunities, and prospects Scholars and practitioners from different disciplines and professional fields have, over the past three decades or so, sought a variety of sustainable urban forms that could contribute to sustainability over the long run in response to the rising concerns about the environment and the socio-economic needs

(Bibri and Krogstie 2017a, b). The compact city (e.g., Jenks et al. 1996a, b; Hofstad 2012; Neuman 2005) and the eco-city (e.g., Joss 2010, 2011; Joss et al. 2013) are the most prevalent models of sustainable urban form and often advocated as more sustainable (e.g., Bibri 2018a, 2019b; Jabareen 2006; Kärrholm 2011; van Bueren et al. 2011; Rapoport and Vernay 2011). These models are compatible and not mutually exclusive, but there are some distinctive concepts and key differences for each one of them (Jabareen 2006). However, the challenge of meeting the goals of sustainable development has induced scholars, planners, policymakers, international organizations, civil societies, and governments to propose these two models as a way of redesigning and restructuring urban areas to achieve sustainability, which have been addressed on different spatial levels, including the regional level, the metropolitan level, the city level, the community level, the neighborhood level, and the building level. However, the underlying challenge continues to induce researchers, practitioners, and decision-makers to work collaboratively to enhance existing models of sustainable urban form across several spatial scales to achieve the requirements of sustainability and, ideally, to integrate its physical, environmental, economic, social, and cultural dimensions (Bibri 2019b). The ultimate goal of the endeavor is to develop more robust models of sustainable urban form. This has indeed been one of the most significant intellectual and practical challenges for more than three decades (e.g., Bibri 2018a, 2019b; Bibri and Krogstie 2017a, b; Jabareen 2006; Kärrholm 2011; Neuman 2005; Williams 2009). As concluded by Jabareen (2006, p. 48) after analyzing a distinctive set of the design principles and strategies as planning and development practices characterizing compact cities and eco-cities, among others, and how these can be compared and classified in terms of their contribution to sustainability, 'neither academics nor real-world cities have yet developed convincing models of sustainable urban form and have not yet gotten specific enough in terms of the components of such form.' This implies that it has been a challenging task to translate sustainability into the built form and, thus, evaluate the extent to which existing models of sustainable urban form contribute to the goals of sustainable development. Indeed, it is not evident which of these models are more sustainable and environmentally sound, although there seems to be in research on sustainable urban forms and anthologies a consensus on topics of relevance to sustainability (e.g., Bibri and Krogstie 2017b), In line with this argument, a critical review of such forms demonstrates a lack of agreement about the most desirable form in the context of sustainability (e.g., Jabareen 2006; Williams et al. 2000). Besides, it is not an easy task to 'judge whether or not a certain urban form is sustainable' (Kärrholm 2011, p. 98). Even in practice, many governments, planning experts, landscape architects, and so on are grappling with the dimensions of models of sustainable urban forms by means of a variety of design, planning, and policy approaches (Jabareen 2006; Kärrholm 2011). In addition, there is a lack of theory that can serve to compare different forms according to their contribution to the goals of sustainable development, as well as to evaluate whether a given urban form contributes to sustainability (Jabareen 2006). In a nutshell, not only in practice, but also in theory and discourse, has the issue of sustainable urban form been problematic and difficult to deal with as manifested in the kind of the non-conclusive, limited, conflicting, contradictory, uncertain, and weak results of research (Jabareen 2006; Kärrholm 2011; Neuman 2005; Williams 2009), particularly when it comes to the actual effects of the benefits of sustainability as assumed or claimed to be produced by design principles and strategies. Conclusively,'yet knowing if we are actually making any progress towards sustainable cities is problematic. In one sense, so much has been achieved in raising the profile of sustainability and sustainable cities over the last 30 years that the rate of change is inspiring… We seem to be going backwards to the extent that it is hard to see where there is any room for optimism. Urban

Table 2 Benefits of smart cities for sustainable cities

Data-driven applications for enhancing the outcome of the design principles and strategies underlying sustainable urban forms
Advanced simulation models for evaluating and optimizing such principles and strategies in terms of design scalability and planning flexibility that are necessary for responding to urban growth, environmental pressures, changes in socio-economic needs, discontinuities, and societal transitions
Urban intelligence functions for monitoring, planning, and designing sustainable cities
Data-driven smart urban metabolism for understanding the causalities governing urbanism and allowing citizens and city authorities to receive feedback on the system consequences of their choices
Innovative frameworks for smartening up urban metabolism to enable sustainable cities to maintain their levels of sustainability
Data-driven approaches to integrating urban systems, coordinating urban domains, and coupling urban networks
Data-driven applications for enhancing participation, equity, fairness, safety, and accessibility, as well as service delivery and efficiency in relation to the quality of life
Data-driven solutions for identifying risks, uncertainties, and hazards

problems…are becoming more acute as populations rise and resources become scarcer.' (Williams 2009, p. 2).

In addition, the conventional sustainable urban planning approach alone is no longer of pertinence as to ensuring or maintaining the effectiveness of sustainable urban forms with regard to the operation, function, and management of urban systems, as well as the integration and coordination of urban domains, in the context of sustainability due to the issues being engendered by the rapid urbanization. In relation to this argument, Neuman (2005) contends, in reference to the fallacy of compact cities, that conceiving cities in terms of forms remains inadequate to achieve the goals of sustainable development; or rather, accounting only for urban form strategies to make cities more sustainable is counterproductive. Instead, conceiving cities in terms of 'processual outcomes of urbanization' holds great potential for attaining these goals, as this involves asking the right question of 'whether the processes of building cities and the processes of living, consuming, and producing in cities are sustainable,' which raises the level of, and may even change, the game (Neuman 2005). The underlying argument is that while the layout or urban form can influence the environmental impact, it is rather the people and their behavior that ultimately determine the negative or positive environmental impact of urban areas. Monitoring, understanding, and analyzing the latter set of processes, in particular, can well be enabled by big data technology as an advanced form of ICT to further improve sustainability. Townsend (2013) portrays urban growth and ICT development as a form of symbiosis. However, the process-driven perspective as to be enabled by big data technology paves the way for a more dynamic conception of urban planning and design that reverses the focus on urban forms governed by static design and planning tools. This holds more promise in attaining the elusive goals of sustainable development (Neuman 2005). Existing models of sustainable urban form as to the underlying design principles and strategies seem to have failed to account for changes over time (Bibri and Krogstie 2017a, b).

In light of the above, it is timely and necessary to apply the innovative solutions and sophisticated approaches being offered by big data technology to deal with the challenges of sustainability as well as urbanization. Besides, a well-established fact is that cities evolve and change dynamically as urban environments, so too is the underlying design and planning knowledge that perennially changes in response to new emergent factors and changes. To put it differently, cities need to be dynamic in their conception, scalable in their design, efficient in their operational functioning, and flexible in their planning in order to be able to deal with population growth, environmental pressures, changes in socio-economic needs, global shifts/trends, discontinuities, and societal transitions (Bibri 2018a, 2019b). Durack (2001) argues for open, indeterminate urbanism due to its advantages, namely the tolerance and value of topographic, social, and economic discontinuities; continuous adaptation; and citizen participation, which is common to human settlements. This alternative approach to planning and development 'recognizes discontinuities and inconsistencies as life-affirming opportunities for adaptation and change, offering choices for the future in accordance with the true definition of sustainability' (Durack 2001, p. 2). This approach is also in line with backcasting as an approach to city planning and development where scenarios are used to explore future uncertainties, create opportunities, build capabilities, and improve decision-making processes, and moreover, when moving step by step towards the vision as visualized in Fig. 1, identify potential stumbling blocks on the way as well as assess policy pathways in terms of planning practices and development strategies necessary to achieve the desired future. Here comes the role of big data technologies and related sophisticated approaches in terms of their incorporation in urban planning and development due to their dynamic, synergistic, disruptive, and substantive effects. This pertains to urban intelligence and planning functions, which represent new conceptions of how smart sustainable cities function and utilize and combine complexity science and urban science in fashioning powerful forms of urban simulations models and optimization and prediction methods that can generate urban forms and structures that improve sustainability, efficiency, resilience, equity, and the quality of life (Bibri 2019b). In addition, In this respect, the provision of data from urban operations and functions is offering the prospect of urban environments wherein the implication of the way smart sustainable cities are functioning and operating is continuously available, and urban planning is facing the prospect of becoming continuous as the data deluge floods from different urban domains and is updated in real time, thereby allowing for a dynamic conception of planning and a scalable and efficient form of design (Bibri 2019b). This new approach also supports the idea of the dynamic conception of planning advanced by Neuman (2005), which emphasizes the processes of building cities and the processes of living, consuming, and producing in cities, rather than conniving cities in terms of forms, to reiterate. All in all, accepting indeterminacy demands much more than settling for the structures of an immutable order, and adopting sustainability as a sincere objective requires planning and developing cities 'not only in closer correspondence with nature, but also in recognition of the process of life itself' (Durack 2001).

Furthermore, in urban planning and policy making, 'the concept of sustainable city has tended to focus mainly on infrastructures for urban metabolism—sewage, water, energy, and waste management within the city' (Höjer and Wangel 2015, p. 3), and thereby falls short in considering smart solutions and sophisticated methods in relation to operational functioning, planning, and design (Bibri 2019b; Bibri and Krogstie 2017b). The concept of urban sustainability has long been promoted by systems scientists using the pragmatic framework for urban metabolism; smart urban metabolism as an ICT-enabled evolution of such framework is being implemented to overcome some of its limitations in the context of eco-city (Shahrokni et al. 2015).

All in all, there are several critical issues that remain unsettled as well as under-explored for applied purposes with regard to the extent to which the challenges of urban sustainability can be addressed, despite the promotion of sustainable cities as a desirable goal within the context of policy and planning. In relation to this, Williams (2009) identifies two fundamental, critical, and interesting challenges pertaining to policies and monitoring strategies. The first is, the challenge of 'the vision': do we know what 'the sustainable city' is? And the second is, the challenge of change: do we know how to bring about 'sustainable urban development'? The latter entails developing a deeper understanding of the multi-faceted processes of change required to achieve more sustainable cities. This relates to the view that there are multiple processes of sustainable urbanism, and hence multiple visions of, and pathways to achieving, the sustainable city. On this note, Williams (2009, p. 3) adds that if we understand and respect this view, 'then we need to accept that making our cities more sustainable will be dependent on a similarly wide-ranging selection of actions. Some actions will be 'top-down' and require strong leadership and, perhaps, large-scale investment programs, other changes may be bottom-up, and rely on…shifts in behavior. These changes…will happen at different paces…, and at difference spatial scales.'

In the above line of thinking, it seems that the eco-city and the compact city as instances of sustainable cities are relatively well understood as a way of practically applying existing knowledge about what makes a city sustainable. Notwithstanding this dominant view in the prescriptive literature, what seems to prevail in research about the relationship between urban design and planning interventions and sustainability objectives is a subject of much debate (Bulkeley and Betsill 2005; Williams 2009). This means that realising an eco-city requires making countless decisions about sustainable (green) technologies, urban layouts, building design, and governance (Rapoport and Vernay 2011), just like the case for compact city (Kärrholm 2011; van Bueren et al. 2011). Furthermore, several studies (e.g., Guy and Marvin 1999; Jabareen 2006; Rapoport and Vernay 2011; van Bueren et al. 2011; Williams 2009) point to the issue of diversity underneath the various uses of the terms eco-city and compact city and shed light on the extent of divergence on the way projects and initiatives conceive of what eco-city and compact city models should be or look like. Indeed, in relation to the compact city, there are great differences between cities in terms of their urban form whose key elements can be distinguished: density, surface, land use, public transport infrastructure, and the economic relationship with the surrounding environment (van Bueren et al. 2011). Similarly, Rapoport and Vernay (2011) determine the differences in the way projects and initiatives conceive of what an eco-city should be. Guy and Marvin (1999) address the issue of the different models and pathways in terms of the diversity of sustainable urban futures. Williams (2009) offers a conceptualization of multiple pathways and processes of sustainable urbanism, and argues that a move to a deeper understanding of the interplay between social and technical solutions for sustainable cities is required. On the whole, there is a great deal of heterogeneity among city initiatives and projects that are considered to be sustainable cities. However, there is a need for recognizing that these multiple pathways and processes of sustainable urbanism need some coherence of purpose. Or else, there will be no conceptual 'anchor' in the event of the continuing conflicts and contradictions within sustainable urbanism thinking and practice, and to this anchor, sustainability principles, the sustainable use and wise management of natural resources, and equity and justice are of high relevance and usefulness. Regardless, understanding the multiplicity and diversity of socially constructed visions of sustainable urbanism is at the heart of stimulating and advancing research and practice, as long as it is driven by some coherence of purpose. In this respect, it has been interesting to witness how many socio-culturally specific ideas have been replicated in different locations across the globe, with little consideration or investigation of their appropriateness (e.g., Williams 2004, 2009). As asserted by Guy and Marvin (1999),'the role of research is to keep alive a multiplicity of pathways by opening a wider discourse and dialogue about the types of future we might be able to create.'

In relation to the ongoing efforts for smartening up sustainable urban forms using big data technology and its application, Bibri (2018a) points out that one of the key scientific and intellectual challenges pertaining to smart sustainable urban forms is to relate the underlying design principles and strategies and thus urban infrastructures to their operational functioning and planning through control, automation, management, and optimization. This relates to new urban intelligence functions as new conceptions of how such forms can function and utilize the complexity sciences in fashioning powerful new forms of simulation models and optimization and prediction methods (on the basis of big data analytics) that generate urban forms and structures that improve sustainability, efficiency, equity, and the quality of life (e.g., Bibri 2019b, d).

The main argument in the ongoing debate over sustainable urban forms as instances of sustainable cities is that urban systems are in themselves very complex in terms of functioning, operation, management, and planning, so too are urban domains in terms of coordination and integration as well as urban networks in terms of coupling and interconnection. Therefore, it is of high relevance to develop and employ innovative solutions for solving, and sophisticated approaches into dealing with, the challenges of sustainability and urbanization. This requires a blend of sciences for creating powerful design and engineering solutions, which ICT is extremely well placed to initiate for its application to urban systems, domains, networks, as well as related processes is founded on computer science, data science, urban science, and complexity science (e.g., Batty et al. 2012; Bibri 2018a, 2019b; Bettencourt 2014). Indeed, the role of ICT-enabled solutions in improving sustainability is becoming evident in light of the ongoing endeavors to advance both sustainable cities and smart cities (see, e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri and Krogstie 2017b; Bettencourt 2014; Kramers et al. 2014; Shahrokni et al. 2015).

All in all, despite the huge advances in different areas of knowledge and a number of impressive practical initiatives and programs in the realm of sustainable urbanism, there is still much more that needs to be done according to what arises of change on the ground. Hence and again, it has become of high significance and importance to theoretically and practically amalgamate the design concepts and planning practices of sustainability with the kind of sophisticated approaches and innovative solutions being offered by big data technology. The ultimate aim is to find more effective ways and more robust methods to improve, advance, and maintain the contribution of sustainable cities to the goals of sustainable development by assessing, optimizing, and enhancing the underlying strategies and approaches using cutting-edge technologies under what is labelled 'smart sustainable cities of the future.' This is important to embrace and pursue in an increasingly computerized and urbanized world. Especially, big data computing is offering great opportunities for, and unsurpassed ways of, effectively monitoring, understanding, analyzing, and planning such cities to achieve the optimal level of sustainability.

Smart cities: realizing the potential of smart cities of the future for advancing sustainability

Since the early 2010s, many scholars have highlighted the crucial role that ICT could play in sustainable urban development by decoupling resource consumption and environmental impact from economic growth while noting that the topic of ICT for sustainability has not attracted actionable political interest as of yet (Bibri 2019a, b). In looking at smart cities through the lens of strategic sustainable development, Colldahl, Frey and Kelemen (2013) note that smart cities hold great potential for advancing sustainability, as it is a powerful approach to enabling cities to become more sustainable due to the role of ICT in providing advanced solutions for addressing the complex challenges and pressing issues of sustainability, in addition to planning cities in a more innovative and forward-thinking manner. In reference to smart cities of the future, Batty et al. (2012) point out that cities can only be smart if there are intelligence functions that are able to integrate and synthesize the data to some purpose, ways of improving efficiency, sustainability, equity, and the quality of life. Future ICT in its form of big data technology and its application is concerned with researching smart cities not simply in terms of their instrumentation: 'constellations of instruments across many scales that are connected through multiple networks which provide continuous data regarding the movements of people and materials in terms of the flow of decisions about the physical and social form of the city' (Batty et al. 2012, p. 482), but also in terms of the way this instrumentation is opening up new opportunities for, and new forms of, advancing sustainability (Bibri 2019a, b).

In light of the above, smart cities have recently gained traction among many national governments and international policymakers as a promising response to the challenges of sustainable development in an increasingly urbanized world. Of particular relevance to emphasize here is that not until more recently that the development of smart cities came to the fore as a sort of panacea for solving the kind of wicked and intractable problems that characterize the practice of urbanism—thanks to the advent of big data technologies and their novel applications for advancing various aspects of sustainability (see, e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bibri 2018a; Bettencourt 2014; Marsal-Llacuna, Colomer-Llinàs and Meléndez-Frigola 2015). In fact, ICT has gained the recognition of offering unsurpassed ways to deal with the environmental, societal, and economic concerns of cities and hence to transform them into urban areas that can adapt to shocks since the mid 1990s, a few years after the widespread diffusion of the concept of sustainable development and the prevalence of ICT worldwide.

ICT has ever science been socially and discursively constructed as having an enabling and catalytic role in sustainable development and in envisioning its future form in the context of sustainable smart cities (Bibri 2019a). In smart cities, ICT is proposed as a set of solutions to urban challenges and issues of a complex nature, including sustainability and living standards (Batty et al. 2012; Hashem et al. 2016). In other words, but in more detail, smart cities represent an urban development paradigm that emerged in the late twentieth century as a result of the drive of cities to be more responsive to citizen needs through offering conditions conducive to promoting and enhancing the quality of life in an increasingly globalized world (Angelidou et al. 2017), and then to become more sustainable in an increasingly urbanized world (International Telecommunications Union (ITU) 2014; UNECE 2015b) with support of advanced ICT.

The assessment of smart cities builds on 'the previous experiences of measuring environmentally friendly and livable cities, embracing the concepts of sustainability and the quality of life but with the important and significant addition of technological and informational components' (Marsal-Llacuna, Colomer-Llinàs and Meléndez-Frigola 2015, cited in Ahvenniemi et al. 2017, p. 235). This relates particularly to big data technology, whose use spans many urban domains with regard to improving operational functioning, monitoring and optimizing infrastructures and facilities, reducing resource consumption, providing efficient and faster services to citizens to enhance the quality of their life, and streamlining planning and decision-making processes, all in line with the goals of sustainable development. By means of ICT innovations and thus advanced smart solutions, cities can well evolve in ways that can address environmental concerns and respond to socio-economic needs in a more strategic manner, as they are the incubators, generators, and transmitters of creative and innovative ideas (Bibri and Krogstie 2017a). The clear prospects of many major cities to overcome the complex challenges pertaining to sustainability and urbanization through the advanced forms of ICT is indeed the key reason why smart cities of the future has recently gained traction as a holistic urban development strategy among universities, research instituters, policymakers, city governments, and industries. When discussing ICT solutions for improving the different aspects of sustainability, reference is often made to smart cities of the future (see, e.g., Batty et al. 2012; Bibri 2018a) This is predicated on the assumption that ICT of pervasive computing offers great opportunities for monitoring, understanding, and analyzing various aspects of urbanity for operating, managing, and planning urban systems in ways that can be leveraged in the needed transition towards, and the advancement of, sustainability. It is in smart cities of the future that the key to a better world—which is held by emerging and future ICT—will be most evidently demonstrated (Batty et al. 2012). The underlying premise is that the use of ICT of pervasive computing, especially big data analytics and its application, is increasingly contributing to the further integration of urban systems and the effective assessment of their performance in terms of sustainability; facilitating collaboration and coordination among urban domains for energy and environmental efficiency gains; enhancing and mainstreaming ecosystem and public and social services; and pinpointing which kinds of networks need to be coupled (Bibri and Krogstie 2017a). This is due to the emerging wave of urban analytics for which big data constitute the fundamental ingredient as well as the opportunity of developing and utilizing new urban intelligence functions for urban monitoring, planning, and design (Bibri 2019b).

Smart sustainable cities: driving factors and research status

We live in a world where ICT has become deeply embedded and interwoven into the very fabric of the contemporary city, i.e., the operating and organizing processes of urban life and thus urban systems and domains are dominated by data and pervaded with information intelligence and high levels of automation and computation. It follows that it is high time for sustainable cities to smarten up in ways that can achieve the optimal level of sustainability. In particular, for sustainable cities to improve, advance, and maintain their contribution to the goals of sustainable development, they need to leverage their informational landscape by embracing what emerging and future ICT has to offer to make urban living more sustainable and attractive over the long run (Bibri and Krogstie 2017b). This is predicated on the assumption that emerging and future ICT offers tremendous potential for, and unsurpassed ways of, monitoring, understanding, analyzing, and planning smart cities and smart sustainable cities of the future to improve sustainability, efficiency, resilience, and the quality of life (Batty et al. 2012; Bibri 2018a). Bibri and Krogstie (2017a) summarize the main benefits of smart cities for sustainable cities (Table 2), which are reframed within the research need for advancing sustainable cities. The purpose is to provide insights into the relevance and usefulness of combining the strengths of sustainable cities and smart cities into an integrated holistic approach to urbanism.

The research on smart sustainable cities is garnering increased attention and rapidly burgeoning, and its status is consolidating as one of the most enticing areas of research today, especially within ecologically advanced nations, making the relevance and rationale behind the smart sustainable city debate highly significant with respect to the future form of urban planning and development. Smart sustainable cities as a holistic approach to urbanism aim primarily at substantiating and strengthening the growing potential and role of advanced ICT in enabling sustainable cities to enhance and maintain their performance in the face of urbanization.The way forward for developing and realizing smart sustainable cities is to amalgamate the sustainable city and smart city landscapes and approaches, a process which typically takes various forms depending on several factors, including objectives, requirements, and resources, as well as the social, cultural, national, and local contexts in which these elements are embedded and hence interpreted as related to urban projects and initiatives (Bibri 2019b). With this multidimensional context in regard, there are, and will be, different ways of conceptualizing and operationalizing the idea of smart sustainable cities and thus multiple pathways to achieve them. On this

Table 3 Problems, issues, and challenges pertaining to sustainable urban forms

What to solve, deal with, or overcome	Deficiencies, limitations, difficulties, fallacies. and uncertainties
Problems	Not only in practice but also in theory have sustainable urban forms been problematic and daunting to deal with as manifested in the kind of the non-conclusive, limited, conflicting, contradictory, uncertain, and weak results of research obtained. This is partly due to the use of traditional collection and analysis methods and data scarcity. These results pertain particularly to the actual effects and benefits of sustainability as assumed or claimed to be delivered by the design principles and strategies adopted in planning and development practices. Sustainable urban forms fall short in considering smart solutions within many urban domains where such solutions could have substantial contributions to the different aspects of sustainability Deficiencies in embedding various forms of advanced ICT into urban design and planning practices associated with sustainable urban forms Sustainable urban forms remain static in planning conception, unscalable in design, inefficient in operational functioning, and ineffective in management without advanced ICT in response to urban growth, environmental pressures, changes in socio-economic needs, global shifts, discontinuities, and societal transitions Realizing compact cities and eco-cities require making countless and complex decisions about green and energy efficient technologies, urban layouts, building design, and governance Divergences in and uncertainties about what to consider and implement from the typologies and design concepts of models of sustainable urban form Sustainable urban forms are in themselves very complex in terms of management, planning, design, and development, so too are their domains in terms of coordination and integration as well as their networks in terms of coupling and interconnection Sustainable cities and smart cities are weakly connected as ideas, visions, and strategies as well as extremely fragmented as landscapes at the technical and policy levels Sustainability goals and smartness targets are misunderstood as to their—rather clear—synergies There is a need for solidifying the existing applied theoretical foundations in ways that provide an explanation for how the contribution of sustainable urban forms to sustainability can be improved and maintained on the basis of big data technology and its applications. There is no strategic model for merging the informational and physical landscapes of the existing models of sustainable urban form.
Issues	In relation to spatial scales, the existing models of sustainable urban forms tend to focus more on the neighbourhood level than on the city level in terms of design and planning due to the uncertainties surrounding the design principles and planning practices as to their actual sustainability effects and benefits Conceiving cities only in terms of forms remains inadequate to achieve the goals of sustainable development. It should be informed by the processual outcomes of urbanization to attain these goals, as this involves asking the right questions related to the behavior of inhabitants; the processes of living, consuming, and producing; and the processes of building urban environments—in terms of whether these are sustainable Cities evolve and change dynamically as complex systems and urban environments, so too is the underlying knowledge of design and planning that is historically determined to change perennially in response to new factors In urban planning and policy making, sustainable cities have tended to focus mainly on infrastructures for urban metabolism—sewage, water, energy, and waste management while falling short in considering innovative solutions and sophisticated methods for urban operational functioning, planning, design, and development
Challenges	One of the most significant challenges is to integrate and augment sustainable urban forms with advanced technologies and their novel applications—in ways that enable them to improve, advance, and maintain its contribution to the goals of sustainable development. There are difficulties in translating sustainability into the built, infrastructural, and functional forms of cities There are difficulties in evaluating the extent to which the existing models of sustainable urban form contribute to the goals of sustainable development. It is not an easy task to even judge whether or not a certain urban form is sustainable One of the key scientific and intellectual challenges pertaining to sustainable urban forms is to relate the underlying typologies and infrastructures to their operational functioning and planning through control, automation, management, optimization, and enhancement There will always be challenges to address and overcome and hence improvements to realize in the field of sustainable cities, and this has much to do with the perception underlying the conceptualization of progress concerning cities. This centers around what we think we are aspiring to, what we assess 'progress' to be, and what changes we want to make

note, Al-Nasrawi et al. (2015) point out that there exists a competition on how to interpret and operationalize the concept of smart sustainable cities. As a corollary of it, there is a great deal of diversity among projects and initiatives considered to be smart sustainable cities in the form of ideas, arguments, or facts. The diversity underneath the various uses of the concept of smart sustainable cities implies that there are both convergences and divergences on the way projects and initiatives conceive of what a smart sustainable city should be in terms of which integrative perspective should be adopted. This can, though, translate into numerous opportunities towards new approaches to smart sustainable urban planning and development in order to mitigate or overcome the current fragmentation of the landscapes of sustainable cities and smart cities. Already, several topical studies (e.g., Angelidou et al. 2017; Bibri 2018a; Bibri and Krogstie 2017b; Kramers et al. 2014; Kramers, Wangel and Höjer 2016; Rivera et al. 2015; Shahrokni et al. 2015; Yigitcanlar and Lee 2013) have addressed the merger of these two landscapes or approaches from a variety of perspectives on how the different forms of advanced ICT can improve various aspects of sustainability, namely ubiquitous computing, big data computing, and/or context-aware computing to advance urban metabolism, urban form (planning and design), urban public and ecosystem services, urban operations and functions, urban strategies and policies, urban governance and citizen participation, or using simply ICT to optimize energy efficiency and provide solutions for everyday life practices. As an example with more detail concerning the conceptualization of the smart sustainable city, Yigitcanlar and Lee (2013) focus on 'ubiquitous-eco-city: a smart-sustainable urban form' whose principal premise is to provide a high quality of life and place to residents with low-to-no negative impacts on the natural environment with support of the state-of-the-art technologies in terms of management, planning, and development. The authors intend to put this premise into a test and address whether u-eco-city is a dazzling smart sustainable urban form that constitutes an ideal 21st century city model. In doing so, they place Korean u-eco-city initiatives under the microscope, as well as critically discuss their prospects in forming a smart sustainable urban form and becoming an ideal city model. Their conceptualization of u-eco-city is illustrated in Fig. 2. U-eco-city is an ICT and eco-technology (EcoT) embedded smart and sustainable city, where people can access both digital and eco-services based on the technology convergence between ICTs and EcoTs (Lee 2009).

All the above endeavors reflect the characteristic spirit and prevailing tendency of the ICT-sustainability-urbanization era as manifested in its aspirations for directing

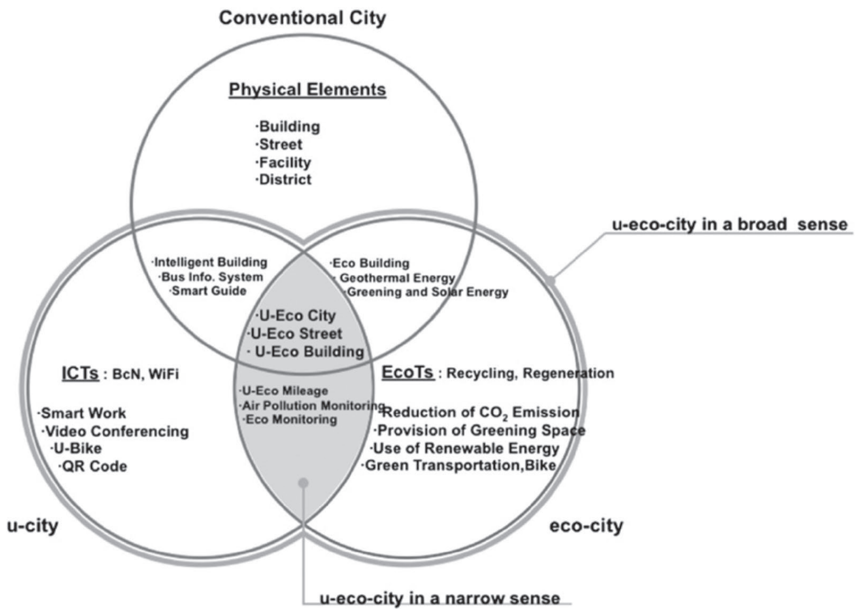

Fig. 2 Relation between ubiquitous-city and eco-city in the context of u-eco-city (source: Yigitcanlar and Lee (2013))

the advances in ICT towards addressing and overcoming the challenges of sustainability and urbanization in the context of smart sustainable cities of the future. All in all, smart sustainable cities open new windows of opportunity for doing a lot more to advance sustainability with support of emerging and future ICT, and offer the types of insights and practical ideas that scholars, practitioners, and policymakers need in order to bring about sustainable urban development.

Furthermore, several ecologically advanced nations aim at or strive for being associated with the concept of smart sustainable cities as a sign of societal development. While some countries claim to have evolved towards smart sustainable cities, and others to have developed the technical infrastructure needed for smart sustainable cities and focused on sustainable development policies, there is no hard evidence to confirm these claims, as there is still no assessment models or advanced frameworks to measure the performance of such cities (Al-Nasrawi et al. 2015). In this respect, Al-Nasrawi et al. (2015) suggest a multidimensional methodological model that assists in evaluating the smartness level of a city while being sensitive to its context, and provide further contribution by combining sustainable and smart dimensions of a city.

In addition, the European Union supports the movement of its cities to being smart (and) sustainable; hence its conscious efforts to drive this by investing in various city initiatives. In relation to the European Innovation Partnership on Smart Cities and Communities website, there are 34 EU projects in different cities concerned with mitigating the various pressures that arise from urban growth and sustainable development. This led to the meeting of the Environment Agency Austria (EAA), the International Telecommunication Union (ITU), EU member states, and other stakeholders in Geneva to come up with and discuss a set of standard indicators to assess a city's path to being smart and sustainable (UNECE, 2015a, b). The Europe 2020 targets serve as a challenge for European cities to improve their competitiveness in terms of how smart, sustainable, and inclusive they are (European Commission 2010b). There has been several efforts toward measuring the systematic progress of cities in achieving these targets, as well as comparing progress made with other cities. One of these efforts is city rankings, which serves as a benchmark that cities can use to measure their overall progress toward well defined targets, as well as to define goals and strategies for future development (Debnath et al. 2014). The indicators jointly proposed by the United Nations Economic Commission for Europe (UNECE) and the International Telecommunications Union (ITU) to rank European capital cities are being used to gauge how smart and sustainable these and other cities are.

All in all, the prospect of smart sustainable cities is becoming the new reality, especially within ecologically advanced nations (Bibri and Krogstie 2016), owing to the underlying global driving factors and prevailing and emerging trends. This development will undoubtedly continue, as it is supported by strong external forces and societal structures affecting the phenomenon of smart sustainable cities. Moreover, it constitutes part of rather larger societal shifts (i.e., sustainability transitions) with far-reaching and long-term implications. This is anchored in the recognition that there are fascinating possibilities and immense opportunities to exploit from deploying and implementing the innovative solutions and sophisticated approaches being offered by big data technology and its novel applications.

The field of smart sustainable cities is a fertile area of interdisciplinary and transdisciplinary research, entailing clearly a wide spectrum of explorable horizons with many intriguing questions awaiting scholars and practitioners from different disciplines and fields (Bibri and Krogstie 2017a). This is underpinned by the recognition that it provides a unique opportunity to take stock and harness the plethora of lessons learned from almost three decades or so of research and planning devoted to seeking, developing, and implementing sustainable cities, and about one decade or so for developing and applying advanced technologies to advance sustainability in smart cities. Therefore, it is high time to leverage the theoretical and substantive knowledge accumulated hitherto on smart sustainable urban planning and development from all kinds of research endeavors as well as projects and initiatives that have contributed to making urban living sustainable and smart.

The outcome of part 2 of strategic problem orientation

Long-lasting trends The key prevailing and emerging trends identified include:

- Global shifts: sustainability, ICT, and urbanization.
- Intellectual discourses: sustainable urbanism, smart urbanism, data-driven urbanism, and sustainable development.
- Academic discourses: sustainable cities, smart cities, and smart sustainable cities.
- Computing paradigms: pervasive computing, ubiquitous computing, the IoT, and big data computing.
- Scientific paradigms: data-intensive science.
- Technological innovations: big data technologies, analytics, and applications.

The dynamic interplay between these varied forms of trends, which will undoubtedly continue to evolve simultaneously and affect one another in a mutual process for many years yet to come, is the backcloth against which many recent urban innovation and transition endeavors have materialized, and hence numerous opportunities have been, and continue to be, created and explored in the context of what has been dubbed data-driven smart sustainable cities. In particular, these forms of trends are shaping and driving not only the materialization of such cities as a leading paradigm of urbanism, but also their evolvement, success, expansion, and evolution.

Problems, issues, and challenges related to sustainable cities Sustainable urban forms have always been problematic and daunting to deal with. In view of that, the intellectual challenge to produce a theoretically and practically convincing model of sustainable urban form with clear components continues to induce scholars, academics, planners, scientists, and even real-world cities to create a more successful and robust model of such form. In addition, the contribution of the existing models of sustainable urban form to sustainability has, over the last three decades or so, been subject to much debate, generating a growing level of criticism that essentially questions their practicality and added value.

Developing a model for smart sustainable cities of the future is aimed at improving, advancing, and maintaining the contribution of sustainable urban forms to the goals of sustainable development with support of big data technologies and their novel applications as advanced forms of ICT. This is due to the underlying potential for enhancing and optimizing urban operations, functions, designs, services, strategies, and practices in line with the goals of sustainable development, as well as for attempting to solve a number of problems, addressing key issues, and overcoming complex challenges in the context of sustainable urban forms. These are distilled and compiled in Table 3 from "Deficiencies, limitations, difficulties, fallacies. uncertainties, opportunities, and prospects" section.

Expected development The main expected developments identified are believed to be already happening or to arrive soon, and include the following:

- Instrumentation, computerization, and computation are routinely pervading the very fabric of sustainable cities.
- Sustainable cities are becoming increasingly datafied and thus dependent upon their data to operate properly—and even to function at all with regard to many domains of urban life—datafication.
- Sustainable urban practices (operational functioning, planning, design, development, and governance) are becoming highly responsive to a form of data-driven urbanism.
- Sustainable cities are increasingly embracing big data technologies and their novel applications to improve, advance, and maintain their contribution to the goals of sustainable development towards achieving the optimal level of sustainability.
- Sustainable cities and smart cities are becoming more and more connected as approaches.
- Smart sustainable cities are gaining foothold and traction worldwide as a promising response to the challenges of sustainability and urbanization.
- Data-driven urbanism is increasingly becoming the mode of production for smart sustainable cities, i.e., a new era is presently unfolding wherein smart sustainable urbanism is increasingly becoming data-driven.
- Data-intensive science as a fourth scientific paradigm is drastically changing how urban analytics and urban studies are done in relation to sustainability science and knowledge.

Discussion and conclusion

Smart sustainable cities as the leading paradigm of urbanism are seen as the most important arena for sustainability transitions. They are well positioned to instigate major, and make significant contributions to, societal transformations by linking sustainable development with technological development. Drastic changes of this kind require long-term versions and thus strategic planning and development where backcasting studies can play a key role in guiding decision-making processes and assessing policy pathways necessary to achieve such visions. Moreover, backcasting studies allow for a better understanding of future opportunities and exploring the implications of alternative development paths that can be relied on to avoid the impacts of the future. When applied in sustainability planning, backcasting can also increase the likelihood to envision certain changes (Holmberg and Robèrt 2000). There is a belief that future-orientated planning can change development paths. The interest in the future of the smart sustainable city is driven by the aspiration to transform the continued urban development path into a sustainable future.

This paper detailed the two parts of strategic problem orientation by answering the guiding questions for Steps 1 and 2 of the futures study being conducted. Important to note, as there are many questions that guide the 6 steps of the backcasting methodology applied in this futures study that need to be answered in a form entailing description, elaboration, explanation, analysis, synthesis, investigation, design, and so on, it is deemed more appropriate to divide the whole scholarly backcasting endeavor into several papers.

Concerning Step 1, the first part of the strategic problem orientation of the backcasting study, the outcome is straightforward. We determined the aim, purpose, and objectives of the backcasting study in relation to the proposed model for smart sustainable cities of the future, and then we specified related sustainability targets and goals. As regards Step 2, the second part of the strategic problem orientation of the backcasting study, a number of a number of different, yet related, forms of trends associated with the phenomenon of smart sustainable cities were identified, described, and elaborated. In addition, the interrelationships between these trends were discussed in relevance to the aim of the futures study. The forms of trends identified include global shifts, intellectual discourses, academic discourses, computing paradigms, scientific paradigms, and technological innovations. Also, envisioning how smart sustainable cities will evolve was supported by the status of the recent and ongoing research endeavors in the field as involving most of the trends identified in this context. Moreover, the causes triggering the various forms of trends to emerge were examined, so was how and why they will continue in that direction. In addition, the key external forces affecting these forms of trends were elucidated and discussed while highlighting that these trends and their amalgamation constitute part of larger societal shifts with far-reaching and long-term implications, namely sustainability transitions.

Remaining on Step 2, the most relevant outcome of the current situation shows that sustainable cities are currently associated with a number of problems, issues, and challenges, and therefore need to embrace what smart cities of the future have to offer in terms of big data technologies and their novel applications in order to improve, advance, and maintain their contribution to the goals of sustainable development. Especially, one of the most significant challenges at the moment is to produce a theoretically and practically convincing and robust model of sustainable urban form with clear components—and seamlessly integrated with advanced technologies and their novel applications (Bibri and Krogstie 2017b). Besides, a large part of research in the area of smart sustainable cities focuses on exploiting the potentials and opportunities of advanced technologies as an effective way to mitigate or overcome the issue of sustainable cities and smart cities being extremely fragmented as landscapes and weakly connected as approaches.

The issue of sustainable urban forms has been problematic. Indeed, the debate over the ideal or desirable urban form dates back to the end of the 19th century, and obviously, the concept of sustainable development revives it and develops existing models of sustainable urban form further by enhancing them with the planning principles and ecological design of sustainability (Jabareen 2006). Again, smart development as being predominately driven by big data technology has recently revived this debate, and is attempting to enhance existing models of sustainable urban form by smartening up the performance of the underlying design principles and strategies, thereby increasing their contribution to sustainability. It has become of high pertinence and importance to augment sustainable urban forms with big data technologies and their novel applications (Bibri and Krogstie 2017b).

Building smart sustainable cities based on big data computing is of a strategic value as to solving many of the complex challenges and pressing issues of sustainability and urbanization. Many sustainable cities across the globe have already started to exploit the potential of big data applications in relation to diverse urban systems and domains. We stand at a threshold of new era where big data science and analytics is drastically changing the way sustainable cities are studied, understood, planned, designed, developed, and governed. The ultimate goal is to improve, advance, and maintain their contribution to sustainability by employing more effective ways to monitor, understand, probe, and plan them. However, there are currently numerous challenges and concerns that need to be addressed and overcome in this new area of science and technology in relation to smart sustainable urbanism for achieving the desired outcomes (see Bibri 2019a for a detailed account).

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Authors' contributions
Both authors read and approved the final manuscript.

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3. Master of Science in computer science with a major in informatics.
4. Master of Science in computer and systems sciences with a major in decision support and risk analysis.
5. Master of Science in entrepreneurship and innovation with a major in new venture creation.
6. Master of Science in strategic leadership toward sustainability.
7. Master of Science in sustainable urban development.
8. Master of Science in environmental science with a major in ecotechnology and sustainable development.
9. Master of Social Science with a major in business administration (MBA).
10. Master of Arts in communication and media for social change.
11. Postgraduate degree (one year of Master courses) in management and economics.
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3. Smart Sustainable Cities of the Future: The Untapped Potential of Big Data Analytics and Context–Aware Computing for Advancing Sustainability (660 pages), Springer, 03/2018.
4. Big Data Science and Analytics for Smart Sustainable Urbanism: Unprecedented Paradigmatic Shifts and Practical Advancements (505 pages), Springer 06/2019.

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Paper 4

Generating a Vision for Smart Sustainable Cities of the Future: A Scholarly Backcasting Approach

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Generating a vision for smart sustainable cities of the future: a scholarly backcasting approach

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Abstract

Sustainable cities have been the leading global paradigm of urbanism. Undoubtedly, sustainable development has, since its widespread diffusion in the early 1990s, positively influenced city planning and development. This pertains to the immense opportunities that have been explored and the enormous benefits that have been realized in relation to sustainable urban forms, especially compact cities and eco-cities. However, such forms are still associated with a number of problems, issues, and challenges. This mainly involves the question of how they should be monitored, understood, analyzed, and planned to improve, advance, and maintain their contribution to sustainability and thus to overcome the kind of wicked problems, unsettled issues, and complex challenges they embody. This in turn brings us to the current question related to the weak connection between and the extreme fragmentation of sustainable cities and smart cities as approaches and landscapes, respectively, despite the proven role of advanced ICT, coupled with the untapped potential of big data technology and its novel applications, in supporting sustainable cities as to enhancing and optimizing their performance under what is labeled "smart sustainable cities." In this respect, there has recently been a conscious push for sustainable cities to become smart and thus more sustainable by particularly embracing what big data technology and its novel applications has to offer in the hopes of reaching the optimal level of sustainability. In the meantime, we are in the midst of an expansion of time horizons in city planning and development. In this context, sustainable cities across the globe have adopted ambitious smart goals that extend far into the future. Essentially, there are multiple visions of, and pathways to achieving, smart sustainable cities based on how they can be conceptualized and operationalized. The aim of this paper is to generate a vision for smart sustainable cities of the future by answering the 6 guiding questions for step 3 of the futures study being conducted. This study aims to analyze, investigate, and develop a novel model for smart sustainable cities of the future using backcasting as a scholarly approach. It involves a series of papers of which this paper is the second one, following the earlier papers with steps 1 and 2. Visionary images of a long-term future can stimulate an accelerated movement towards achieving the long-term goals of sustainability. The proposed model is believed to be the first of its kind and thus has not been, to the best of one's knowledge, produced, nor is it being currently investigated, elsewhere.

Keywords: Smart sustainable cities, Sustainable cities, Smart cities, Compact cities, Eco-cities, Data-driven cities, Big data computing and the underpinning technologies, Future vision, Backcasting, Futures studies

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Introduction

Contemporary cities have a pivotal role in strategic sustainable development; therefore, they have gained a central position in operationalizing this notion and applying this discourse. This is clearly reflected in the Sustainable Development Goal 11 (SGD 11) of the United Nations' 2030 Agenda, which seek to make cities more sustainable, resilient, inclusive, and safe [73]. Sustainable cities have long been the leading global paradigm of urbanism [19, 74, 77–79] for more than three decades or so. The subject of "sustainable cities" remains endlessly fascinating and enticing, as there are numerous actors involved in the academic and practical aspects of the endeavor, including engineers and architects, green technologists, built and natural environment specialists, and environmental and social scientists, and, more recently, computer scientists, data scientists, and urban scientists. All these actors are undertaking research and developing strategies and programs to tackle the challenging elements of sustainable urbanism. This adds to the work of policymakers and political decision-makers in terms of formulating and implementing regulatory policies and devising and applying political mechanisms and governance arrangements to promote and spur innovation and monitor and maintain progress in sustainable cities.

Since its widespread diffusion in the early 1990s, sustainable development has had significant positive impacts on the planning and development of cities in terms of the different dimensions of sustainability. It has also revived the discussion about the form of cities [40]. In this regard, it has inspired a whole generation of urban scholars and practitioners into a quest for the immense opportunities and fascinating possibilities that could be enabled and created by, and the enormous benefits that could be realized from, the planning and development of sustainable urban forms (especially compact cities and eco-cities), That is to say, forms for human settlements that can meet the required level of sustainability and enable the built environment to function in a constructive way. This can be accomplished through continuously improving their contribution to the goals of sustainable development in terms of reducing material use, lowering energy consumption, mitigating pollution, and minimizing waste, as well as in terms of improving equity, inclusion, the quality of life, and well-being.

However, new circumstances require new responses. This pertains to the spread of urbanization and the rise of ICT and how they are drastically changing sustainable urbanism. The transformative force of urbanization and ICT and the role that cities can play have far-reaching implications. By all indicators, the urban world will become largely technologized and computerized within just a few decades, and ICT as an enabling, integrative, and constitutive technology of the twenty-first century will accordingly be instrumental, if not determining, in addressing many of the conundrums posed, the issues raised, and the challenges presented by urbanization. It is therefore of strategic value to start directing the use of emerging ICT into understanding and proactively mitigating the potential effects of urbanization, with the primary aim of tackling the many intractable and wicked problems involved in urban operational functioning, management, planning, development, and governance, especially in the context of sustainability. Indeed, the rapid urbanization of the world poses significant and unprecedented challenges associated with sustainability (e.g., [26, 31, 34]) due to the issues engendered by urban growth. In short, the multidimensional effects of unsustainability are most likely to exacerbate with urbanization. Urban growth will jeopardize the sustainability of cities [53]. Therefore, ICT has come to the fore and become of crucial importance for containing the effects of urbanization and facing the challenges of sustainability, including in the context of sustainable cities which are striving to improve, advance, and maintain their contribution to the goals of sustainable development. The use of advanced ICT in sustainable cities constitutes an effective approach to decoupling the health of the city and the quality of life of citizens from the energy and material consumption and concomitant environmental risks associated with urban operations, functions, services, strategies, and policies [13].

Smart sustainable cities as an integrated and holistic approach to urbanism represent an instance of sustainable urban planning and development, a strategic approach to achieving the long-term goals of urban sustainability—with support of advanced technologies and their novel applications. Accordingly, achieving the status of smart sustainable cities epitomizes an instance of urban sustainability. This notion refers to a desired (normative) state in which a city strives to retain a balance of the socio-ecological systems through adopting and executing sustainable development strategies as a desired (normative) trajectory [19]. This balance entails enhancing the physical, environmental, social, and economic systems of the city in line with sustainability over the long run—given their interdependence, synergy, and equal importance. This long-term strategic goal requires, as noted by [7], p. 601), "fostering linkages between scientific research, technological innovations, institutional practices, and policy design and planning in relevance to sustainability. It also requires a long-term vision, a trans-disciplinary approach, and a system-oriented perspective on addressing environmental, economic, social, and physical issues." All these requirements are at the core of backcasting as a scholarly and planning approach to futures studies. This approach facilitates and contributes to the development, implementation, evaluation, and improvement of models for smart sustainable cities, with a particular focus on practical interventions for integrating and improving urban systems and coordinating and coupling urban domains using cutting-edge technologies in line with the vision of sustainability. One of the most appealing strands of research in the domain of smart sustainable urbanism is that which is concerned with futures studies. The relevance and rationale behind futures research approach are linked to the strategic planning and development associated with long-term sustainability endeavors, initiatives, or solutions. And backcasting is well suited to any multifaceted kind of planning and development process (e.g., [38]), as well as to dealing with urban sustainability problems and challenges [19, 23, 29, 52, 59].

The aim of this paper is to generate a vision for smart sustainable cities of the future by answering the 6 guiding questions for step 3 of the futures study being conducted, namely:

- What are the terms of reference for the future vision?
- How does the future sustainable socio-technical system and need fulfillment look like?
- How is the future vision different from the existing socio-technical systems?
- What is the rationale for developing the future vision?
- Which sustainability problems, issues, and challenges have been dealt with by meeting the stated objectives and thus achieving the specified goals?
- Which advanced technologies and their novel applications have been used in the future vision?

This futures study aims to analyze, investigate, and develop a novel model for smart sustainable cities of the future using backcasting as a scholarly approach. It consists of 6 steps in total and a number of guiding questions for each step to answer. Accordingly, it involves a series of papers of which this paper is the second one, following the earlier papers with steps 1 and 2: strategic problem orientation [19]. This paper as a sequel leads through the whole of the backcasting study: step 4 with 2 papers, step 5 with 1 paper, and step 6 with 1 paper. All in all, as this is an extensive scholarly project involving description, investigation, synthesis, design, analysis, and compilation, it is deemed more appropriate to divide it into a series of papers.

The remainder of this paper is structured as follows. Section 2 provides a background of the futures study, including a review of the area being researched, the issue of the current situation, and studies and relevant history on the issue. Section 3 focuses on the backcasting methodology, with an emphasis on step 3. Section 4 delves into step 3 of the futures study by answering the 6 guiding questions in more detail following the applied backcasting approach. This paper ends, in Section 5, with discussion and conclusion.

Background of the futures study

Sustainable cities are associated with a number of problems, issues, and challenges (i.e., deficiencies, Limitations difficulties, fallacies, and uncertainties) when it comes to their management, planning, design, development, and governance in the context of sustainability (e.g., [16, 17, 19, 27, 28, 54]). This mainly involves the question of how sustainable urban forms should be monitored, understood, and analyzed in order to be effectively planned, designed, developed, managed, and governed in terms of enhancing and maintaining their sustainability performance [13]. The underlying argument is that more innovative solutions and sophisticated approaches are needed to overcome the kind of wicked problems, unsettled issues, and complex challenges pertaining to sustainable urban forms. This brings us to the current question related to the weak connection of and extreme fragmentation between sustainable cities and smart cities as approaches and landscapes, respectively (e.g., [3, 7, 13, 16, 19, 20, 49]), despite the great potential of advanced ICT for, and its proven role in, supporting sustainable cities in improving their performance under what is labeled "smart sustainable cities" (e.g., see, [7, 8, 17, 49, 68]). In particular, tremendous opportunities are available for utilizing big data computing and the underpinning technologies and their novel applications in sustainable cities to improve, advance, and maintain their contribution to the goals of sustainable development. The main strength of the big data technology is the high influence it will have on many facets of smart sustainable cities and their citizens' lives (see, e.g., [2–4, 6, 8, 13, 58, 71]).

In light of the above, recent research endeavors have started to focus on smartening up sustainable cities through enhancing and optimizing their operational functioning, management, planning, design, development, and governance in line with the long-term vision of sustainability under what is labeled "smart sustainable cities"([7–9, 12, 16, 17, 19], Bibri and Krogstie 2017c). This wave of research revolves around integrating the landscapes of, and the approaches to, sustainable cities and smart cities in a variety of ways in the hopes of reaching the required level of sustainability and improving the living standard of citizens [13]. This integrated approach tends to take several forms in terms of combining the strengths of sustainable cities and smart cities based on how the concept of smart sustainable cities can be conceptualized and operationalized, just as it has been the case for sustainable cities. Indeed, several topical studies (e.g., [3, 7, 8, 13, 17, 49, 50, 62, 68, 81]) have addressed the merger of the sustainable city and smart city approaches from a variety of perspectives. Accordingly, there is a host of opportunities yet to explore towards new approaches to smart sustainable urbanism. The focus in this paper is on integrating the design principles and planning practices of sustainable urban forms with big data computing and the underpinning technologies and their novel applications being offered by smart cities of the future. The underlying assumption is that the evolving big data deluge with its extensive sources hides in itself the answers to the most challenging analytical questions as well as the solutions to the most complex challenges pertaining to sustainability in the face of urbanization. It also plays a key role in understanding urban constituents as data agents.

In recent years, there has been a marked intensification of datafication. This is manifested in a radical expansion in the volume, range, variety, and granularity of the data being generated about urban environments and citizens (e.g., [46–48]), with the primary aim of quantifying the whole of the city, putting it in a data format so it can be organized and analyzed [13]. We are currently experiencing the accelerated datafication of the city in a rapidly urbanizing world and witnessing the dawn of the big data era not out of the window, but in everyday life. Our urban everydayness is entangled with data sensing, data processing, and communication networking, and our wired world generates and analyzes overwhelming and incredible amounts of data. The modern city is turning into constellations of instruments and computers across many scales and morphing into a haze of software instructions, which are becoming essential to the operational functioning, planning, design, development, and governance of the city. The datafication of spatiotemporal citywide events has become a salient factor for the practice of smart sustainable urbanism.

As a consequence of datafication, a new era is presently unfolding wherein smart sustainable urbanism is increasingly becoming data-driven. At the heart of such urbanism is a computational understanding of urban systems and processes that renders urban life a form of logical rules and algorithmic procedures—which is underpinned and informed by data-intensive scientific approaches to urban science and urban sustainability, while also harnessing urban big data to provide a more holistic and integrated view and synoptic intelligence of the city [13]. This is increasingly directed towards improving, advancing, and maintaining the contribution of sustainable cities to the goals of sustainable development in an increasingly urbanized world.

We are living at the dawn of what has been termed as “the fourth paradigm of science,” a scientific revolution that is marked by the recent emergence of big data science and analytics as well as the increasing adoption and use of the underlying technologies in scientific and scholarly research practices. Everything about science development and knowledge production is fundamentally changing thanks to the unfolding and soaring data deluge. The upcoming data avalanche is thus the primary fuel of this new age, which powerful computational processes or analytics algorithms are using to generate useful knowledge and deep insights pertaining to a wide variety of practical uses.

As a new area of science and technology, “big data science and analytics embodies an unprecedentedly transformative power—which is manifested not only in the form of revolutionizing science and transforming knowledge, but also in advancing social practices, catalyzing major shifts, and fostering societal transitions. Of particular relevance, it is instigating a massive change in the way both sustainable cities and smart cities are understood, studied, planned, operated, and managed to improve and maintain sustainability in the face of expanding urbanization” ([14], p. 79). To put it differently, these practices are becoming highly responsive to a form of data-driven urbanism that is the key mode of production for what have been termed smart sustainable cities whose monitoring, understanding, and analysis are increasingly relying on big data technologies.

In a nutshell, the Fourth Scientific Revolution is set to erupt in cities, break out suddenly and dramatically, throughout the world. This is manifested in bits meeting bricks on a vast scale as instrumentation, datafication, and computerization are permeating the spaces we live in. The outcome will impact most aspects of urban life, raising questions and issues of urgent concern, especially those related to sustainability and urbanization. This pertains to what dimensions of cities will be most affected; how urban planning, design, development, and governance should change and evolve; and, most importantly, how cities can embrace and prepare for looming technological disruptions and opportunities.

In light of the above, at the beginning of a new decade, we have the opportunity to look forward and consider what we could achieve in the coming years in the era of big data revolution. Again, we have the chance to consider the desired future of data-driven smart sustainable cities. This will motivate many urban scholars, scientists, and practitioners to think about how the subject of “data-driven smart sustainable cities” might develop, as well as inspire them into a quest for the immense opportunities and fascinating possibilities that can be created by the development and implementation of such cities. In this respect, we are in the midst of an expansion of time horizons in city planning. Sustainable cities look further into the future when forming scenarios and strategies to achieve them. The movement towards a long-term vision arises from three major mega trends or macro-shifts that shape our societies at a growing pace: sustainability, ICT, and urbanization. Recognizing a link between such trends, sustainable cities across the globe have adopted ambitious goals that extend far into the future and developed different pathways to achieve them.

Backcasting as a scholarly approach to strategic smart sustainable city planning and development

As a special kind of scenario methodology, backcasting is applied here to build a future model for smart sustainable cities as a planning tool for facilitating urban sustainability. Backcasting scenarios are used to explore future uncertainties, create opportunities, build capabilities, and improve decision-making processes. Their primary aim is to discover alternative pathways through which a desirable future can be reached. Following Rotmans et al.'s [65] taxonomy, scenarios can be classified into different categories, including projective and prospective scenarios, qualitative and quantitative scenarios, participatory and expert scenarios, and descriptive and normative scenarios. This futures study is concerned with a normative scenario, which takes values and interests (sustainability and big data technology) into account and involves reasoning from specific long-term goals that have to be achieved.

In general, the backcasting approach is applicable in futures studies dealing with the fundamental question of backcasting, which involves the kind of actions that must be taken to achieve a long-term goal. In this context, if we want to attain a smart sustainable city, what actions must be taken to get there? Here backcasting means to look at the current situation from a future perspective. As an analytical and deliberative process (Fig. 1), backcasting entails articulating an end vision and then developing a pathway to get from the present to that endpoint. In more detail, the backcasting scenario is constructed from the distant future towards the present by defining a desirable future and then moving step-by-step backwards towards the present to identify the strategic steps that need to be taken to attain that specified future. This involves identifying the stumbling blocks on the way and the key stakeholders that should be involved to drive change, as well as developing and assessing the policy pathway in terms of planning practices and development strategies necessary to achieve the future outcome. The use of backcasting in futures studies assumes a vision of an evolutionary process of policy with a time frame of a generation or so, which is a basic principle to allow the policy actions to pursue the path towards, and potentially achieve, a sustainable future. Moreover, in urban sustainability, planning is about figuring out the 'next steps' which are quite literally the next concrete actions to undertake. Next steps are usually based on reacting to present circumstances, creativity, intuition, and common sense, but also (conceivably) are still aligned with the future vision and direction. Therefore, researchers in backcasting should not get obsessed with the next steps without considering how aligned they are with what they ultimately aim to achieve.

Figure 1 illustrates the backcasting process in which the future desired conditions are envisioned and steps are then defined to attain those conditions. In this regard, envisioning the smart sustainable city as a future vision has a normative side: what future is desired? Backcasting this preferred vision has an analytical side: how can this desirable future be attained? Backcasting is about analyzing possible ways of attaining certain futures as well as their feasibility and potential [56]. Specifically, in the quest for the answer to how to reach specified outcomes in the future, backcasting involves finding ways of linking goals that may lie far ahead in the future to a set of steps to be taken now and designed to achieve that end, and also facilitates discovery [29].

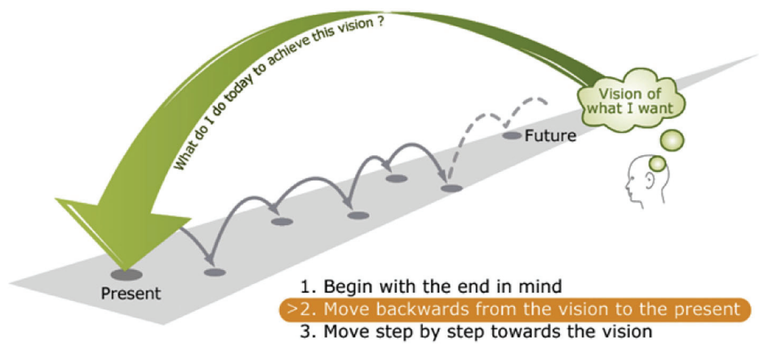

Fig. 1 The backcasting process from the natural step. Source: Holmberg [37]

Backcasting is viewed as a natural step in operationalizing sustainable development [38] within different societal spheres. In terms of its practical application, backcasting is increasingly used in futures studies in the fields related to sustainable urban planning as a formal element of future strategic initiatives. It is the most applied approach in futures studies when it comes to sustainability problems and the identification and exploration of their solutions. This involves a wide variety of areas, including strategic city planning (e.g., [59]), sustainable city design [23]. transportation and mobility (Banister et al. 2000), sustainable transportation systems (Akerman and Höjer 2006; [39, 66]), sustainable technologies and sustainable system innovation [76], sustainable household (Green and Vergragt 2002; [57]), and sustainable transformation of organizations [37]. Backcasting studies must reflect solutions to a specified social problem in the broader sense [29]. Bibri [10] concludes that the backcasting approach is found to be well-suited for long-term urban sustainability problems and solutions due to its normative, goal-oriented, and problem-solving character. Generally, as argued by Dreborg [29], backcasting is particularly useful when:

- The problem to be studied is complex and there is a need for major change
- The dominant trends are part of the problem
- The problem to a great extent is a matter of externalities
- The scope is wide enough and time horizon is long enough to leave considerable room for deliberate and different choices and directions of development.

Bibri [10] has recently conducted a comprehensive study on futures studies and related approaches. Its main focus is on backcasting as a scholarly and planning approach to strategic smart sustainable city development. Its main objectives are to review the existing backcasting methodologies and to discuss the relevance of their use in terms of their steps and guiding questions for analyzing, investigating, and developing smart sustainable cities, as well as to synthesize a backcasting approach based on a number of notable future studies. Later, Bibri and Krogstie [19] adapted the approach, i.e., made minor changes so as to improve and clarify it in accordance with the overall aim of this futures study as well as the specificity of the proposed model. Indeed, a commonly held view is that the researchers' worldview and purpose remain the most important criteria for determining how futures studies can be developed and conducted in terms of the details concerning the questions guiding the steps involved in a particular backcasting approach. This helps to identify and implement strategic decisions associated with urban sustainability. However, the outcome of the adapted synthesized approach is illustrated in Table 1.

As the focus in this paper is on step 3, it is important to point out that the backcasting approach is traditionally based on one normative vision, but multiple visions can also be used to explore different future alternatives (e.g., [72]). In this futures study, step 3 of backcasting constructs only one future vision based on the objectives, goals, and targets specified in step 1, indicating an integrated solution to a set of problems and challenges associated with existing sustainable urban forms, with support of advanced technologies. In addition, the development of the future vision is typically performed after the stage of analyzing the current situation and assessing the external factors (steps 1 and 2 of the backcasting study). While some views defend that a prior evaluation grounds the vision in realism, others argue that it curtails the ability to think of "ideal states" by putting the current circumstances and capabilities at the center of attention. However, this prescribed vision of the future is based on a sequential progression into the future of the current trends and the expected developments and the way they intertwine with and affect one another in relation to smart sustainable cities, without sharp transformation. It is also based on a combination of technological innovations and sustainability advancements, or on the co-evolutionary pathways of social and ecological systems.

Future vision generation

Constructing the future vision entails defining and describing a desirable future in which the problems and issues identified in relation to existing sustainable urban forms have been solved by meeting the stated objectives and thus achieving the specified goals and targets described in step 1 (see [19] for a detailed account and discussion). In general, future vision construction is about identifying the desired future state, which consists of vibrant descriptions of audacious goals and targets, as well as reflective statements addressing the aspired future. It is important to note at this stage that the vision of the future and the proposed novel model tend to be used interchangeably in this paper. Indeed, this vision represents a short and concise version of this model. In other words, this model entails a desired future state that is supposed to be more detailed at the end of this scholarly backcasting endeavor.

On the visionary approach (see guiding question 1)

The future vision is a result of the concept of urban sustainability as clarified, advocated, and advanced by many scholars, academics, theorists, and practitioners in the field, and demonstrated in numerous real-world cities across the globe, especially within ecologically advanced nations. According to several rankings, Sweden, Norway, Finland, Germany, and the Netherlands have the highest

Table 1 The guiding questions for each step in the backcasting study

Questions for backcasting steps	Methods
Step 1: Detail strategic problem orientation (part 1)	Study design and problem formulation
1. What is the socio-technical system to be studied?	
2. What are the aim, purpose, and objectives of the futures study in relation to this system?	
3. What are the long–term targets declared by the goal-oriented backcasting approach?	
4. What are the goals of sustainability these targets are translated to for scenario analysis?	
Step 2: Detail strategic problem orientation (part 2)	Trend analysis and problem analysis
1. What are the key trends and expected developments related to the socio-technical system to be studied?	
2. What are the major problems, issues, and challenges of sustainability and the underlying causes—the current situation?	
3. How is the problem defined and what are the possible problem perceptions?	
Step 3: Generate a sustainable future vision	Creativity method
1. What are the demands (terms of reference) for the future vision?	
2. How does the future sustainable socio-technical system and need fulfillment look like?	
3. How is the future vision different from the existing socio-technical systems?	
4. What is the rationale for developing the future vision? 5. Which sustainability problems, issues, and challenges have been solved	
6. or mitigated by meeting the stated objectives and thus achieving the specified targets and goals? 7. Which advanced technologies and their novel applications have been	
8. used in the future vision?	
Step 4: Conduct empirical research	Case study method
1. What category of case studies is most relevant to the future vision?	
2. How many case studies are to be conducted and what kind of phenomena do they intend to illuminate?	
3. What is the rationale for the methodological approach adopted?	
4. To what extent can this empirical research generate new ideas and serve to illustrate the theories and their effects underlying the future vision so as to underpin its potential and practicality?	
Step 5: Specify and merge the components of the socio-technical system to be developed	Creativity method
1. What specific design concepts, planning practices, and technology elements are necessary?	
2. What kind of urban centers and labs are necessary?	
3. What spatial dimensions and scale stabilizations should be considered?	
4. How can all of the ingredients be integrated into a model for strategic smart sustainable city planning and development?	
Step 6: Perform backcasting backward-looking analysis	Backcasting analysis
1. What urban and technological changes are necessary for achieving the future vision?	
2. What structural, institutional, and regulatory changes are necessary?	
3. How have the necessary changes been realized and what stakeholders are necessary?	
4. What are the opportunities, potentials, benefits, and other effects of the future vision?	

level of sustainable development practices (e.g, [30]). However, the development of the novel model for smart sustainable cities of the future is supported by several case studies from Sweden as well as their integration in terms of the planning practices and development strategies through which sustainable urban forms can be achieved. Additionally, this model involves the way instrumentation, datafication, and computerization are opening up dramatically different forms of optimizing and enhancing the performance of such forms, thereby increasing their contribution to the goals of sustainable development. This entails the ways in which the informational landscape of smart cities as underpinned by big data technologies and their novel applications can be integrated with the physical landscape of sustainable cities, and what this implies in regard to increasing their sustainability benefits. The essence of the idea revolves around the need to harness, analyze, and leverage the deluge of urban data that has hitherto been mostly associated with smart cities but has clear synergies in the functioning, planning, and development of sustainable cities in terms of improving, advancing, and maintaining their contribution to sustainability.

The problems and issues that the sustainable city faces today will, especially if its landscape and strategy continues to be extremely fragmented from and weakly connected with those of the smart city at the technical and policy levels, increase in the future with possibly much greater compounding effects due to the rapid urbanization of the world and the mounting challenges of sustainability in a rather increasingly technologized and computerized world. As a scholarly endeavor, the development of the novel model for smart sustainable cities of the future as a holistic approach to city planning and development is primarily aimed at bringing together and interlinking the sustainable city and smart city landscapes and strategies so as to address and overcome a set of challenging problems associated with the existing sustainable urban forms. This requires finding more creative and effective ways of merging sustainability knowledge with advanced technologies to enhance the performance of such forms in the face of urbanization using cutting-edge technologies. This can be accomplished by amalgamating the compact city with the eco-city into one model of sustainable urban form in terms of the underlying typologies and design concepts as planning practices, and then augmenting this model with big data technologies and their novel applications as a set of innovative solutions and sophisticated approaches being offered by the data-driven city. In this respect, city operating system, operations centers, innovation and living labs, and strategic planning and policy offices will handle the activity of generating, processing, and analyzing the data deluge aimed at adopting those innovation solutions and sophisticated approaches in the context of the smart sustainable city. Practical uses and applications in this regard span a range of urban systems and domains in terms of operations, functions, services, designs, strategies, and policies with respect to sustainability.

The future vision has a high expectation on big data technology to deliver the needed solutions and approaches to meet the optimal level of sustainability and enable the built environment to function in a more constructive way than at present in terms of lowering energy consumption, mitigating pollution, and minimizing waste, as well as in terms of improving equity, inclusion, and the quality of life. This is to be determined by whether and the extent to which a given city is currently badging or regenerating itself as, or manifestly planning to be, sustainable or smart sustainable. And what this entails in terms of long-term targets of sustainable development as set by that city, in particular in connection with its design concepts, typologies, spatial organizations, and scale stabilizations as planning practices. In the short term, although big data technology could theoretically help meet the optimal level of sustainability and enable the instrumentation, datafication, and computerization of the built environment towards purposeful urban functioning and planning, this would be difficult and expensive. Nevertheless, the future vision can be feasible because it has to be realized over the long run.

The technological vision is based on the assumption of a full development, integration, and deployment of big data computing and the underpinning technologies which exist today and are likely to become widely available in the years ahead to achieve the sought goals. The incorporation of these advanced technologies into urban environments is supported by their untapped potential for and proven role in overcoming the problems and challenges of urbanization and sustainability. In this respect, big data computing and the underpinning technologies will be determining in the process of redesigning and restructuring urban places to achieve the optimal level of sustainability.

The future vision (see guiding question 2)

The key goal to be necessarily present in any backcasting endeavor is generating the normative alternative for the future and, as related to step 5 which is to be addressed in one of the upcoming papers, analyzing its opportunities, potentials, environmental and social benefits, and other effects.

Taking the prevailing and emerging trends to the extreme with the main expected developments (the outcome of step 2) in mind, we singled out one major societal driver for one scenario: a situation that is most likely to happen in the future:

A scenario where innovations and advancements in big data science and analytics and the underpinning technologies as a disruptive form of science and technology dramatically changes the rules by which society functions on a global scale.

Accordingly, the futures study envisions the smart sustainable city as:

> A form for human settlements that will be able to improve, advance, and maintain its contribution to the goals of sustainable development by being pervaded, monitored, understood, and analyzed by advanced ICT. As such, it is to be realised by the planning practices and design strategies pertaining

to the most advocated and prevalent models of sustainable urban form as integrated—as well as underpinned by big data computing and the underlying core enabling technologies in terms of the instrumentation, datafication, and analytics of the built environment. Related sophisticated approaches and novel applications will be developed, applied, and enhanced by a number of strategic urban actors, including urban operations centers, urban services agencies, strategic planning and design offices, policymaking bodies, research centers, and innovation and living labs. The main strategic goal of the future model of data–driven smart sustainable urban form is to secure and uphold environmentally sound, socially beneficial, and economically viable development towards achieving sustainability.

In light of the above, envisaging the smart sustainable city of the future focuses on the urban and technological components and how they should be integrated that make the city functions as a smart sustainable entity as well as a social organism. Central to this quest is the idea of big data computing and the underpinning technologies as an advanced form of ICT penetrating wherever and whatever it can of the built environment to improve and sustain the performance of what and how urban stakeholders can envision and enact in terms of new forms of cities with regard to sustainability. Furthermore, advanced ICT comes into play as a response to the commonly held view that cities should be conceived in terms of both urban strategies and processual outcomes of urbanization, which involves questions related to the behavior of inhabitants; the processes of living, consuming, and producing; and the processes of building urban environments—in terms of whether these are sustainable. The underlying assumption is that conceiving cities only in terms of, or accounting only for, urban strategies to make cities more sustainable remains inadequate to achieve the elusive goals of sustainable development.

The three strands of the model for smart Sustainable City of the future (see guiding question 3)

As hinted at above, the novel model for smart sustainable cities of the future, the more detailed version of the future vision, integrates two models of sustainable urban form: the compact city and the eco-city, with the data-driven city. This will result in a holistic approach to urbanism, which is different, to a great extent, from these cities taken separately as existing approaches to urbanism. Worth pointing out, to reiterate, is that the focus of this amalgamation is on the design concepts and typologies characterizing both the compact city (i.e., compactness, density, diversity, mixed-land use, and sustainable transport) and the eco-city (i.e., renewable resources, passive solar design, ecological and cultural diversity, greening, environmental management, and other key environmentally sound policies) together with the innovative solutions and sophisticated approaches being offered by big data technologies and their novel applications for sustainability, which relate to the data-driven city and its components (i.e., urban operating centers, research centers, living labs, and innovation labs). The nature and scope of this amalgamation are to be determined by how and the extent to which the characteristic features of the data-driven city would dovetail with those of the integrated model of sustainable urban form towards producing what can be described as—data-driven smart sustainable urban form. The possible steps to be taken to attain the smart sustainable city of the future as a desired end-point or future vision is rather the object of step 5 of the backcasting approach, which comes after step 4. This step is concerned with the case studies that need to be performed to strengthen the future vision and thus the novel model with empirical investigation. The guiding questions of these two steps are listed in Table 1.

Furthermore, it must be noted that there are neither real examples of a truly smart sustainable city that have actually been delivered and thus no precedents to reference, nor future-proofing of the big data technology to ensure that it is able to be adapted, modified, and built upon in an effective way over the next 25 years or so in response to the dynamic changes of technology and fast-moving hi-tech industry. Therefore, the planned big data technology solutions must be evaluated through actual implementation and its successfulness in order to outline the actual opportunity pertaining to the improvement and advancement of urban sustainability. Indeed, big data computing and the underpinning technologies intended to support the smart sustainable city of the future are currently evolving along with those experts and professionals who are needed to support and operate them; sustainability objectives, goals, and directives are increasingly being, and should continue to be, supported and facilitated using this advanced technology as much as possible across urban domains in terms of operations, functions, services, designs, strategies, and policies; and citizens and communities must be involved and engaged with big data technology and related platforms on a far broader scale. The road ahead promises to be an exciting one as more cities become aware of the great potential and clear prospect of integrating the smart city and the sustainable city as landscapes and strategies. In the sequel, we describe the three strands that comprise the novel model for smart sustainable cities of the future as hinted at in the description of the vision of the future above.

Sustainable cities

There are multiple views on what a sustainable city should be or look like and thus various ways of defining or conceptualizing it. Generally, a sustainable city can be understood as a set of approaches into operationalizing sustainable development in, or practically applying the knowledge about sustainability and related technologies to the planning and design of, existing and new cities or districts. It represents an instance of sustainable urban development, a strategic approach to achieving the long-term goals of urban sustainability. Accordingly, it needs to balance between the environmental, social, and economic goals of sustainability as an integrated process. Specifically, as put succinctly by [11], p. 11), a sustainable city "strives to maximize the efficiency of energy and material use, create a zero-waste system, support renewable energy production and consumption, promote carbon-neutrality and reduce pollution, decrease transport needs and encourage walking and cycling, provide efficient and sustainable transport, preserve ecosystems and green space, emphasize design scalability and spatial proximity, and promote livability and community-oriented human environments."

There are different instances of sustainable cities as an umbrella term, which are identified as models of sustainable urban forms, including compact cities, eco-cities, sustainable urbanism, green urbanism, new urbanism, and urban containment, with the first two being often advocated as the most sustainable and environmentally sound models [13]. In addition, Jabareen [40] ranks compact cities as more sustainable than eco-cities from a conceptual perspective using a thematic analysis. However, the effects of these models are compatible with the goals of sustainable development in terms of transport provision, mobility and accessibility, travel behavior, energy conservation, pollution and waste reduction, economic viability, life quality, and social equity. Furthermore, there are multiple definitions of compact cities and eco-cities in the literature (e.g., [40–45, 54, 60, 61, 64, 74]). These definitions tend to be based on the wider socio-cultural context in which these models of sustainable urban form are embedded in the form of projects and initiatives and related objectives, requirements, resources, and capabilities. In other words, there is a diversity underneath the various uses of the term compact city and eco-city, as well as a convergence or divergence in the way projects and initiatives conceive of what these city approaches should be.

The compact city model The concept of the compact city became widespread in the early 1990s as a result of the near clinical separation of land uses because of suburban sprawl that had risen the need for mobility, creating an upsurge in automobile use, which in turn caused high levels of air and noise pollution, as well as decaying city centers. In the 1990s, the European Commission highlighted a number of negative trends in urban development in their Green Paper on the Urban Environment [24], and therefore argued for denser development, mixed land use, and the transformation of former brownfield sites rather than development in open green areas. Fundamentally, the compact city is characterized by high-density and mixed-land use with no sprawl [41, 42, 80] through the intensification of development, i.e., infill, renewal, redevelopment, and so on. It was around the mid-1990s when the research led to the advocacy of combining compactness and mixed-land use [40]. Mixed-land use should be encouraged in cities [21]. In addition, the compact city emphasizes spatial diversity, social mix, sustainable transportation (e.g., transit-rich interconnected nodes), as well as high standards of environmental and urban management systems, energy-efficient buildings, closeness to local squares, more space for bikes and pedestrians, and green areas [17, 19]. It has been addressed and can be implemented at different levels, namely neighborhood, district, city, metropolitan, and region, and involves many strategies that can avoid all the problems of modernist design in cities by enhancing the underlying environmental, social, and economic justifications and drivers. Neuman [54] identifies and enumerates the key dimensions of the compact city in Table 2.

Table 2 Compact city dimensions. Source: Neuman [54]

Compact city dimensions
1. High residential and employment densities
2. Mixture of land uses
3. Fine grain of land uses (proximity of varied uses and small relative size of land parcels)
4. Increased social and economic interactions
5. Contiguous development (some parcels/structures may be vacant or abandoned or surface parking)
6. Contained urban development, demarcated by legible limits
7. Urban infrastructure, especially sewerage and water mains
8. Multimodal transportation
9. High degrees of accessibility: local/regional
10. High degrees of street connectivity (internal/external), including sidewalks and bicycle lanes
11. High degree of impervious surface coverage
12. Low open-space ratio
13. Unitary control of planning of land development, or closely coordinated control
14. Sufficient government fiscal capacity to finance urban facilities and infrastructure

The compact city is more energy efficient and less polluting because people live in close proximity to workplaces, shops, and leisure and service facilities, which enables them to walk, bike, or take transit. This is in turn anticipated to create a better quality of life by creating more social interaction, community spirit, and cultural vitality (Jenks and Jones 2010). Further, travel distances between activities are shortened due to the heterogeneous zoning that enables compatible land uses to locate in close proximity to one another—mixed-land uses. Such zoning primarily reduces the use of automobiles (car dependency) for commuting, leisure, and shopping trips [1, 75]. Integrating land use, transport, and environmental planning is key to minimizing the need for travel and to promoting efficient modes of transport [67]. Transport systems play particularly an important role in the livability of contemporary cities [55]. The interrelationship between transport, people, and amenities are argued to be the vital elements of the microstructure of a sustainable city [32]. Important to note is that population densities are sufficient for supporting local services and businesses [80] in terms of economic viability. In high-density development, more land is available for green and agricultural areas, public transport services are superior, and the environmental footprint of the non-renewable resource consumption is steady [69].

In sum, the compact city model has been advocated as more sustainable urban form due to several reasons: "First, compact cities are argued to be efficient for more sustainable modes of transport. Second, compact cities are seen as a sustainable use of land. By reducing sprawl, land in the countryside is preserved and land in towns can be recycled for development. Third, in social terms, compactness and mixed uses are associated with diversity, social cohesion, and cultural development. Some also argue that it is an equitable form because it offers good accessibility. Fourth, compact cities are argued to be economically viable because infrastructure, such as roads and street lighting, can be provided cost-effectively per capita." ([40], p. 46).

The eco-city model The idea of the eco-city is widely varied in conceptualization and operationalization, and also difficult to delineate. According to the most comprehensive survey of eco-cities to date performed by Joss [43], the diversity and plurality of the projects and initiatives reflected in the use of the term "eco-city" across the globe make it difficult to develop a meaningful definition. Therefore, the concept of the eco-city has taken on many definitions in the literature. Richard Register, an architect widely credited as the first to have coined the term, describes an eco-city as "an urban environmental system in which input (of resources) and output (of waste) are minimized" [61]. Joss [44] states that an eco-city must be, using three analytical categories, developed on a substantial scale, occurring across multiple domains, and supported by policy processes. As an umbrella metaphor, the eco-city "encompasses a wide range of urban-ecological proposals that aim to achieve urban sustainability. These approaches propose a wide range of environmental, social, and institutional policies that are directed to managing urban spaces to achieve sustainability. This type promotes the ecological agenda and emphasizes environmental management through a set of institutional and policy tools." ([40], p. 47) This implies that realizing an eco-city requires making countless decisions about urban design, governance, sustainable technologies, and so on [60]. This in turn signifies that the relationship between sustainable development objectives and urban planning interventions is a subject of much debate [22, 79].

Irrespective of the way the idea of the eco-city has been conceptualized and operationalized, there are still some criteria that have been proposed to identify what a desirable or ideal "eco-city" is or looks like, comprising the environmental, social and economic goals of sustainable development. Roseland [64] and Harvey [35] describe an ideal "eco-city" as a city that fulfills the following requirements:

- Operates on a self-contained local economy that obtains resources locally
- Maximizes energy and water efficiency, thereby promoting conservation of resources
- Manages an ecologically beneficial waste management system that promotes recycling and reuse to create a zero-waste system
- Promotes the use and production of renewable energy, thereby being entirely carbon-neutral
- Has a well-designed urban city layout that promotes walkability, biking, and the use of public transportation systems
- Ensures decent and affordable housing for all socio-economic and ethnic groups and improves jobs opportunities for disadvantaged groups
- Supports urban and local farming
- Supports future progress and expansion over time.

As added by Graedel [33], the eco-city is scalable and evolvable in design in response to urban growth and need changes. Based on these characteristic features, the eco-city and green urbanism overlap or share several concepts, ideas, and visions in terms of the role of the city and positive urbanism in shaping more sustainable places, communities, and lifestyles [5], pp. 6–8, cited in [40]) views, while arguing for the need for new approaches to urbanism to incorporate more ecologically responsible forms of living and settlement, a city exemplifying green urbanism as one that:

- strives to live within its ecological limits;
- is designed to function in ways analogous to nature;
- strives to achieve a circular rather than a linear metabolism;
- strives towards local and regional self-sufficiency;
- facilitates more sustainable lifestyles; and
- emphasizes a high quality of neighborhood and community life.

The eco-city approaches tend to emphasize different aspects of sustainability, namely passive solar design, greening, sustainable housing, sustainable urban living, and living machines [40]. Worth noting is that, as a general consensus, the eco-city is eco-amorphous (formless) in terms of typologies, although it emphasizes passive solar and ecological design [40]. Indeed, it is evident that the form specificities are on less focus in eco-city development. That is to say, the built environment of the city in terms of urban design features and spatial organizations is insignificant, unlike the compact city which focuses on the spatial patterns of physical objects. Rather, what counts most is how the city as a social fabric is organized, managed, and governed. In this line of thinking, [70], p. 37), state, 'social, economic, and cultural variables are far more important in determining the good city than any choice of spatial arrangements.' In view of that, the focus is on the role of different environmental, social, economic, institutional, and land use policies in managing and governing the city to achieve the required level of sustainability (e.g., [25, 40, 63]).

The data-driven city and its smart and sustainable dimensions

"Data-driven smart sustainable cities" is a term that has recently gained traction in academia, government, and industry to describe cities that are increasingly composed and monitored by ICT of ubiquitous and pervasive computing and thus have the ability of using advanced technologies by city operations centers, strategic planning and policy offices, research centers, innovation labs, and living labs for generating, processing, and analyzing the data deluge in order to enhance decision making processes and to develop and implement innovative solutions for improving sustainability, efficiency, resilience, equity, and the quality of life [13]. It entails developing a citywide instrumented system (i.e., inter-agency control, planning, innovation, and research hubs) for creating and inventing the future. For example, a data-driven city operations center, which is designed to monitor the city as a whole, pulls or brings together real-time data streams from many different agencies spread across various urban domains and then analyze them for decision making and problem solving purposes: optimizing, regulating, and managing urban operations (e.g., traffic, transport, mobility, energy, etc.).

As cities are routinely embedded with all kinds of ICT forms, including infrastructures, platforms, systems, devices, sensors and actuators, and networks, the volume of data generated about them is growing exponentially and diversifying, providing rich, heterogenous streams of information about urban environments and citizens. This data deluge enables a real-time analysis of different urban systems and interconnects data to provide detailed views of the relationships between various forms of data that can be utilized for improving the various aspects of urbanity through new modes of operational functioning, planning, development, and governance in the context of sustainability.

On the evolving integration of data-driven, smart, and sustainable cities Cities are becoming ever more computationally augmented and digitally instrumented and networked, their systems interlinked and integrated, their domains combined and coordinated, and their networks coupled and interconnected, and consequently, vast troves of urban data are being generated and used to regulate, control, manage, and organize urban life in real time. In other words, the increasing pervasiveness of urban systems, domains, and networks utilizing digital technologies is generating enormous amounts of digital traces capable of reflecting in real time how people make use of urban spaces and infrastructures and how urban activities and processes are performed. This informational asset is being leveraged in steering cities. Indeed, citizens leave their digital traces just about everywhere they go, both voluntarily and involuntarily, and when cross-referenced with each citizen's spatial, temporal, and geographical contexts, the data harnessed at this scale offers a means of describing, and responding to, the dynamics of the city in real time. In addition to individual citizens, city systems, domains, and networks constitute the main source of data deluge, which is generated by various urban entities, including governmental agencies, authorities, administrators, institutions, organizations, enterprises, and communities by means of urban operations, functions, services, designs, strategies, and policies.

Smart cities are increasingly connecting the ICT infrastructure, the physical infrastructure, the social infrastructure, and the economic infrastructure to leverage their collective intelligence, thereby striving to render themselves more sustainable, efficient, functional, resilient, livable, and equitable. It follows that smart cities of the future seek to solve a fundamental conundrum of cities—ensure sustainable socio-economic development, equity, and enhanced quality-of-life at the same time as reducing costs and increasing resource efficiency and environment and infrastructure resilience. This is increasingly enabled by utilizing a fast-flowing torrent of urban data and the rapidly evolving data analytics technologies; algorithmic planning and governance; and responsive, networked urban systems. In particular, the generation of colossal amounts of data and the development of sophisticated data analytics for understanding, monitoring, probing, regulating, and planning the city are significant aspects of smart cities that are being embraced by sustainable cities to improve, advance, and maintain their contribution to the goals of sustainable development (e.g., [8, 13, 17, 18]). Indeed, there has recently been much enthusiasm in the domain of smart sustainable urbanism about the immense possibilities and fascinating opportunities created by the data deluge and its extensive sources with regard to optimizing and enhancing urban operational functioning, management, planning, design, and development in line with the goals of sustainable development as a result of thinking about and understanding sustainability and urbanization and their relationships in a data-analytic fashion for the purpose of generating and applying knowledge-driven, fact-based, strategic decisions in relation to such urban domains as transport, traffic, mobility, energy, environment, education, healthcare, public safety, public services, governance, and science and innovation. For supra-national states, national governments, and city officials, smart cities offer the enticing potential of environmental and socio-economic development, and the renewal of urban centers as hubs of innovation and research (e.g., [2, 4, 13, 19, 46, 51, 71]). While there are several main characteristics of a smart city as evidenced by industry and government literature (e.g., [36, 46] for an overview), the one that the futures study, and thus this paper, is concerned with focuses on environmental and social sustainability.

A framework for the data-driven smart sustainable city The framework for the data-driven smart sustainable city illustrated in Fig. 2 entails specialized urban, technological, organizational, and institutional elements dedicated for improving, advancing, and maintaining the contribution of such city to the goals of sustainable development [13]. It is derived based on thematic analysis and technical literature. This justifies the relationship between the underlying components. Furthermore, underlying the idea of the data-driven smart sustainable city is the process of drawing all the kinds of analytics associated with urban life into a single hub, supported by the broader public and open data analytics. This involves creating a city-wide instrumented or centralized system that draws together data streams from many agencies (across city domains) for large scale analytics and then direct them to different centers, labs, and offices. Urban operating systems explicitly link together multiple urban technologies to enable greater coordination of urban systems and domains. Urban operations centers attempt to draw together and interlink urban big data to provide integrated and holistic views and synoptic city intelligence through processing, analyzing, visualizing, and monitoring the vast deluge of urban data that can be used for real-time decision-making pertaining to sustainability by means of big data ecosystems. Strategic planning and policy centers serve as a data analytic hub to weave together data from many diverse agencies to control, manage, regulate, and govern urban life more efficiently and effectively in relation to sustainability. This entails an integration that enables systemwide effects to be understood, analyzed, tracked, and built into the very designs and responses that characterize urban operations, functions, and services. As far as research centers and innovation labs are concerned, they are associated with research and innovation for the purpose of developing and disseminating urban intelligence functions. For the anatomy of the data-driven smart sustainable city in terms of digital instrumentation, datafication, computerization, as well as urban operations centers, strategic planning and policy offices, living labs, innovations labs, urban intelligence functions, and so on, the reader can be directed to Bibri [15].

The rationale behind developing the future vision (see guiding question 4)

The arguments, a set of reasons given in support of the novel model for smart sustainable cities of the future, are compiled and distilled from the outcome of step 2 of the backcasting study conducted by Bibri and Krogstie [19]. There are many reasons for integrating the existing models of sustainable urban form as a set of practices, or many explanations of controlling the concepts and principles of these practice in the domain of urban sustainability. This applies also to the integration of the sustainable city and the data-driven city as different approaches to urbanism. Here, we identify the key reasons in relevance to the aim of the futures study. This is accordingly to justify the research pursuit of analyzing, investigating, and developing the proposed model for smart sustainable city of the future.

Amalgamating the compact city model with the eco-city model

- Being one of the most significant intellectual and practical challenges for three decades, the development of a desirable model of sustainable urban form continues to motivate and inspire collaboration between researchers, academics, and

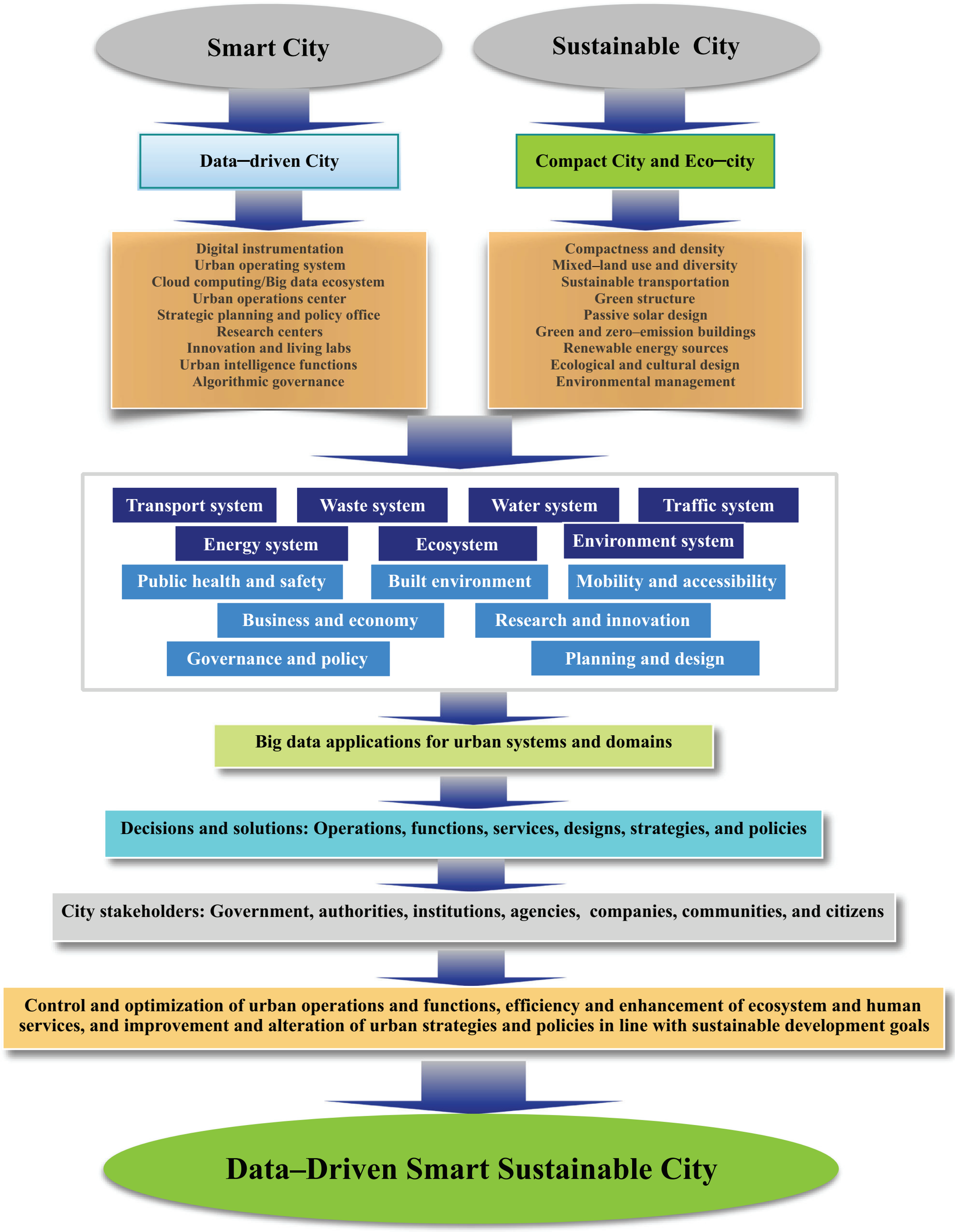

Fig. 2 A framework for the data-driven smart sustainable city. Source: Adapted from Bibri [15]

practitioners to create more effective design and planning solutions based on a more integrated and holistic perspective.
- Different scholars and planners may develop different combinations of design concepts to achieve the goals of sustainable development. They might come with different forms, where each form emphasizes different concepts and contributes differently to sustainability.
- Sustainable urban forms have many overlaps among them in their concepts, ideas, and visions. While there is nothing wrong with such forms being different yet compatible and not mutually exclusive, it can extremely be beneficial and strategic to find innovative ways of combining their distinctive concepts and key differences towards more holistic forms for improving sustainability performance.
- Compact cities have a form as they are governed by static planning and design tools, whereas eco-cities are amorphous: without a clearly defined form, thereby the feasibility and potential of their integra tion into one model that can eventually accelerate sustainable development towards achieving the optimal level of sustainability.
- Neither real-world cities nor academics have yet developed convincing models of sustainable urban form, and the components of such form are still not yet fully specified.
- More in-depth knowledge on planning practices is needed to capture the vision of sustainable urban development, so too is a deeper understanding of the multi-faceted processes of change to achieve sustainable urban forms. This entails conceptualizing multiple pathways towards attaining this vision and developing a deeper understanding of the interplay between social and technical solutions for sustainable urban forms.

Merging the integrated model of sustainable urban form with the data-driven smart city model

- Smart urbanism as being predominately driven by big data computing and the underpinning technologies has recently revived the debate about sustainable cities, and promises to add a whole new dimension to sustainability by enhancing the outcome of the design principles and strategies underlying the existing models of sustainable urban form in ways that enable such form to achieve the optimal level of sustainability.
- It is an urban world where the physical landscape of sustainable cities and the informational landscape of smart cities are increasingly being merged. Hence, it is high time for sustainable urban forms to embrace and leverage what data-driven smart cities have to offer in terms of innovative solutions and sophisti cated approaches to overcome the complex challenges of sustainability and urbanization.
- A large part of research within the emerging area of smart sustainable cities focuses on exploiting the potentials and opportunities of advanced technologies and their novel applications to mitigate or overcome the issue of sustainable cities and smart cities being extremely fragmented as landscapes and weakly connected as approaches, especially at the technical and policy levels.
- There is huge potential for using big data computing and the underpinning technologies to advance sustainable urban forms through novel approaches to decision support in the form of intelligence functions enabled by the analytical power of the deluge of urban data.
- Tremendous opportunities are available for utilizing big data applications in sustainable cities to optimize and enhance their operations, functions, services, designs, strategies, and policies, as well as to find answers to challenging analytical questions and thereby advance knowledge.
- As an integrated and holistic approach, smart sustainable cities tend to take multiple forms of combining the strengths of sustainable cities and smart cities based on how the concept of smart sustainable cities can be conceptualized and operationalized. As a corollary of this, there is a host of unexplored opportunities towards new approaches to smart sustainable urban development.

Problems, issues, and challenges (see guiding question 5)

The issue of sustainable urban forms has always been problematic and daunting to deal with. In view of that, the intellectual challenge to produce a theoretically and practically convincing model of sustainable urban form with clear components continues to induce scholars, academics, planners, scientists, and real-world cities even to create a more successful and robust model of such form. In addition, the contribution of the existing models of sustainable urban form to sustainability has, over the last three decades or so, been subject to much debate, generating a growing level of criticism that essentially questions its practicality, intellectual foundation, and added value.

Developing the model for smart sustainable cities of the future is aimed at improving, advancing, and sustaining the contribution of sustainable urban forms to the goals of sustainable development with support of big data computing and the underpinning technologies as an advanced form of ICT. This is due to the underlying potential for enhancing and optimizing urban operations, functions, designs, services, strategies, and practices in line with the goals of sustainable development, as well as for solving a number of problems, addressing key issues, and overcoming complex challenges in the context of sustainable urban forms. These are distilled and compiled from an extensive interdisciplinary literature review and the outcome of step 2 of the backcasting study ([16, 19]) (Table 3).

Key novel analytical and practical applications of big data technology for the future vision (see guiding question 6)

Big data applications are increasingly permeating the systems and domains of sustainable cities. This can be seen as a new ethos added to the era of sustainable urbanism in response to the rise of ICT and the spread of urbanization as major global shifts at play today. The characteristic spirit of this era is manifested in the behavior and aspiration of sustainable cities towards

Table 3 Problems, issues, and challenges pertaining to sustainable urban forms

What to solve, deal with, or overcome	Deficiencies, Limitations difficulties, fallacies, and uncertainties
Problems	• Not only in practice but also in theory have sustainable urban forms been problematic and daunting to deal with as manifested in the kind of the non-conclusive, limited, conflicting, contradictory, uncertain, and weak results of research obtained. This is partly due to the use of traditional collection and analysis methods and data scarcity. These results pertain particularly to the actual effects and benefits of sustainability as assumed or claimed to be delivered by the design principles and strategies adopted in planning and development practices. • Sustainable urban forms fall short in considering smart solutions within many urban domains where such solutions could have substantial contributions to the different aspects of sustainability. • Deficiencies in embedding various forms of advanced ICT into urban design and planning practices associated with sustainable urban forms. • Sustainable urban forms remain static in planning conception, unscalable in design, inefficient in operational functioning, and ineffective in management without advanced ICT in response to urban growth, environmental pressures, changes in socio-economic needs, global shifts, discontinuities, and societal transitions. • Realizing compact cities and eco-cities require making countless and complex decisions about green and energy-efficient technologies, urban layouts, building design, and governance. • Divergences in and uncertainties about what to consider and implement from the typologies and design concepts of models of sustainable urban form. • Sustainable urban forms are in themselves very complex in terms of management, planning, design, and development, so too are their domains in terms of coordination and integration as well as their networks in terms of coupling and interconnection. • Sustainable cities and smart cities are weakly connected as ideas, visions, and strategies as well as extremely fragmented as landscapes at the technical and policy levels. • Sustainability goals and smartness targets are misunderstood as to their—rather clear—synergies. • There is a need for solidifying the existing applied theoretical foundations in ways that provide an explanation for how the contribution of sustainable urban forms to sustainability can be improved and maintained on the basis of big data technology and its applications. • There is no strategic framework for merging the informational and physical landscapes of the existing models of sustainable urban form.
Issues	• In relation to spatial scales, the existing models of sustainable urban forms tend to focus more on the neighbourhood level than on the city level in terms of design and planning due to the uncertainties surrounding the design principles and planning practices as to their actual sustainability effects and benefits. • Conceiving cities only in terms of forms remains inadequate to achieve the goals of sustainable development. It should be informed by the processual outcomes of urbanization to attain these goals, as this involves asking the right questions related to the behavior of inhabitants; the processes of living, consuming, and producing; and the processes of building urban environments—in terms of whether these are sustainable. • Cities evolve and change dynamically as complex systems and urban environments, so too is the underlying knowledge of design and planning that is historically determined to change perennially in response to new factors. • In urban planning and policy making, sustainable cities have tended to focus mainly on infrastructures for urban metabolism—sewage, water, energy, and waste management while falling short in considering innovative solutions and sophisticated methods for urban operational functioning, planning, design, and development.
Challenges	• One of the most significant challenges is to integrate and augment sustainable urban forms with advanced technologies and their novel applications—in ways that enable them to improve, advance, and maintain its contribution to the goals of sustainable development. • There are difficulties in translating sustainability into the built, infrastructural, and functional forms of cities. • There are difficulties in evaluating the extent to which the existing models of sustainable urban form contribute to the goals of sustainable development. It is not an easy task to even judge whether or not a certain urban form is sustainable. • One of the key scientific and intellectual challenges pertaining to sustainable urban forms is to relate the underlying typologies and infrastructures to their operational functioning and planning through control, automation, management, optimization, and enhancement. • There will always be challenges to address and overcome and hence improvements to realize in the field of sustainable cities, and this has much to do with the perception underlying the conceptualization of progress concerning cities. This centers around what we think we are aspiring to, what we assess “progress” to be, and what changes we want to make.

embracing what big data computing and the underpinning technologies have to offer in order to bring about sustainable development and thus achieve sustainability under what is labeled "smart sustainable cities of the future." The range of the emerging big data applications as novel analytical and practical solutions that can be utilized for enhancing the sustainability performance of sustainable cities is potentially huge. A recent study conducted by Bibri [13] reveals that tremendous opportunities are available for utilizing big data applications to improve, advance, and maintain the contribution of sustainable cities to the goals of sustainable development. This finding is based on identifying, synthesizing, distilling, and enumerating the most common big data applications in relation to a number of urban domains or sub-domains, as well as elucidating their sustainability effects associated with the underlying functionalities pertaining to these domains or sub-domains. These specifically include transport and traffic, mobility, energy, power grid, environment, buildings, infrastructures, urban planning, urban design, governance, healthcare, education, public safety, and academic and scientific research.

The potential of big data technology lies in enabling sustainable cities to harness and leverage their informational landscape in effectively understanding, monitoring, probing, and planning their systems in ways that enable them to achieve the optimal level of sustainability. To put it differently, the use of this advanced technology is projected to play a significant role in realizing the key characteristic features of such cities, namely the efficiency of operations and functions, the efficient utilization of natural resources, the intelligent management of infrastructures and facilities, the lowering of pollution and waste, the improvement of the quality of life and well-being of citizens, and the enhancement of mobility and accessibility.

Discussion and conclusion

Long-lasting and substantive transformations such as sustainability transitions can only come about through the accumulation of several integrated smaller-scale actions associated with strategically successful initiatives and programs. The backcasting approach to futures studies can help to highlight such initiatives and programs, and also play a key role in sustaining the momentum in the quest to bring about major transformations. In the context of city planning and development, this approach can be used to illustrate what might happen to cities in order to allow them to adapt to perceived future trends and to manage uncertainty. As such, it aids in dealing with this uncertainty by clarifying what the most desirable possibilities are, what can be known, what is already known, as well as how today's decisions may play out in each of a variety of plausible futures. Futures studies using backcasting approaches allow for a better understanding of future opportunities and exploring the implications of alternative development paths that can be relied on to avoid the impacts of the future. There is a strong belief that future-orientated planning can change development paths. The interest in the future of smart sustainable cities is driven by the aspiration to transform the continued urban development path. Therefore, it is worthy to venture some thoughts about where it might be useful to channel the efforts now and in the future in relation to smart sustainable urban planning and development. The backcasting scenario, a description of possible actions in the future, starts with constructing the vision of the future and then works backwards in time step-by-step to figure out how this future could emerge as a particular "desired end-point" through identifying the necessary steps to reach it.

This paper aimed to generate a vision for smart sustainable cities of the future by answering the 6 guiding questions for step 3 of the futures study being conducted. We described the terms of reference for the future vision under the visionary approach. These terms entail the scope and limitation of the area of knowledge to be focused on and the description of the structure and objectives of the futures study. Then, we described how the future vision look like, more specifically, the novel model for smart sustainable cities of the future and its role in achieving the optimal level of sustainability. Following this, we detailed how the proposed model is different from existing approaches to urbanism, namely compact cities, eco-cities, data-driven smart cities by describing and discussing the three strands that comprise this model, as well as how they intertwine with one another in the context of sustainability. This was justified by providing the rationale for developing the future vision, which represents the short and concise version of the respective model. Of particular importance, we provided a tabulation version of the review and discussion of the sustainability problems and issues that are supposed to be tackled by meeting the objectives stated and thus achieving the goals specified in step 1 of the backcasting study. In relation to this, we provided an account of the kind of technologies and their novel applications that are intended to be used as part of the proposed model.

Working with a long-term image of the future is meant to increase the possibilities of, and accelerate the movement towards, reaching a smart sustainable city. In this regard, the novel model for smart sustainable cities of the future will be the boost to new forms of policy analysis and planning in the era of big data revolution, and the greatest impacts of big data technology will be on the way we improve, advance, and maintain the contribution of sustainable cities to the goals of sustainable development in the future by means of integrating urban strategies and technological innovations. The main goal of big data technology is to provide intelligence functions that will make this possible in the most effective ways.

Worth pointing out is that smart sustainable cities as an integrated model take multiple forms of combining the strengths of sustainable cities and smart cities based on how the concept of smart sustainable cities can be conceptualized and operationalized. Just as it has been the case for sustainable cities: there are multiple visions of, and pathways towards achieving, sustainable urban development. As a corollary of this, there is a host of unexplored opportunities towards new approaches to smart sustainable urban planning and development. These future endeavors reflect the characteristic spirit and prevailing tendency of the ICT-sustainability-urbanization era as manifested in its aspirations for directing the advances in ICT of pervasive computing towards addressing and overcoming the challenges of sustainability and urbanization in the defining context of smart sustainable cities of the future.

Similarly, in relation to backcasting as a planning approach, multiple visions can be used to explore different future alternatives as to smart sustainable cities. It is important, though, to take into consideration that big data technologies as part of future visions seem to be deurbanized in the sense of not being made to work within a particular urban context, or to be tailored to different urban landscapes and strategies. Besides, it is unfeasible simply to plop down advanced technologies and force them to work in a given urban space. Cities are so characterized by key specificities such that technology systems might work in one city and not be desirable in another, unless they are dramatically reworked or reshaped to be practical in those cities where they have to be implemented. Hence, there is a need for urbanizing big data technologies and in different directions, we content and advocate, when it comes to generating future visions. With that in mind, the future vision this paper is concerned with pertains to cities in ecologically and technologically advanced nations.

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Authors' contributions
Both authors read and approved the final manuscript.

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3. Master of Science in computer science with a major in informatics
4. Master of Science in computer and systems sciences with a major in decision support and risk analysis
5. Master of Science in entrepreneurship and innovation with a major in new venture creation
6. Master of Science in strategic leadership towards sustainability
7. Master of Science in sustainable urban development
8. Master of Science in environmental science with a major in ecotechnology and sustainable development
9. Master of Social Science with a major in business administration (MBA)
10. Master of Arts in communication and media for social change
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1. The Human Face of Ambient Intelligence: Cognitive, Emotional, Affective, Behavioral and Conversational Aspects (525 pages), Springer, 07/2015.
2. The Shaping of Ambient Intelligence and the Internet of Things: Historico-epistemic, Socio-cultural, Politico-institutional and Eco-environmental Dimensions (301 pages), Springer, 11/2015.
3. Smart Sustainable Cities of the Future: The Untapped Potential of Big Data Analytics and Context-Aware Computing for Advancing Sustainability (660 pages), Springer, 03/2018.
4. Big Data Science and Analytics for Smart Sustainable Urbanism: Unprecedented Paradigmatic Shifts and Practical Advancements (505 pages), Springer, 06/2019.

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Paper 5

A Methodological Framework for Futures Studies: Integrating Normative Backcasting Approaches and Descriptive Case Study Design for Strategic Data-Driven Smart Sustainable City Planning

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A methodological framework for futures studies: integrating normative backcasting approaches and descriptive case study design for strategic data-driven smart sustainable city planning

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Abstract

Originally proposed as an alternative to traditional energy planning methodology in the 1970s, backcasting is increasingly applied in futures studies related to sustainability, as it is viewed as a natural step in operationalizing sustainable development. This futures study is concerned with data-driven smart sustainable urbanism as an instance of sustainable urban development—a strategic approach to achieving the long-term goals of urban sustainability. This is at the core of backcasting, which typically defines criteria for a desirable (sustainable) future and builds a set of feasible and logical pathways between the state of the future and the present. This paper reviews, discusses, and justifies the methodological framework applied in the futures study. This aims to analyze, investigate, and develop a novel model for data-driven smart sustainable cities of the future as a form of transformative change towards sustainability. This paper corroborates that the backcasting approach—as applied in the futures study—is well-suited for long-term urban problems and sustainability solutions due to its normative, goal-oriented, and problem-solving character. It also suggests that case study research is the most effective way to underpin and increase the feasibility of future visions. Indeed, the case study approach as a research strategy facilitates the investigation and understanding of the underlying principles in the real-world phenomena involved in the construction of the future vision in the backcasting study. The novelty of this work lies in the integration of a set of principles underlying several normative backcasting approaches with descriptive case study design to devise a framework for strategic urban planning whose core objective is clarifying which city model is desired and working towards that goal. Visionary images of a long-term future based on normative backcasting can spur innovative thinking about and accelerate the movement towards sustainability. The proposed framework serves to help researchers in analyzing, investigating, and developing future models of sustainable urbanism, smart urbanism, and smart sustainable urbanism, as well as to support policymakers and facilitate and guide their actions with respect to transformative changes towards sustainability based on empirical research.

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Keywords: Normative backcasting, Descriptive case study, Futures studies, Data-driven smart sustainable cities, Strategic planning, Energy planning, Methodology

Introduction

In recent years, there has been a conscious push for sustainable cities across the globe to be smarter and thus more sustainable by developing and implementing data-driven technology solutions so as to optimize and enhance their operations, functions, services, designs, strategies, and policies in line with the vision of sustainability. Big data technologies are becoming essential to the functioning of sustainable cities (e.g., Bibri 2018a, b, 2019a, b, 2020a, b, c, d; Bibri and Krogstie 2017a, b, 2018, 2020a; Pasichnyi et al. 2019; Shahrokni et al. 2014a, b, 2015a, b; Sun and Du 2017). Consequently, a new era is presently unfolding wherein sustainable urban development processes and practices are being highly responsive to a form of data-driven urbanism under what is labelled "data–driven smart sustainable cities."

As an emerging paradigm of urbanism, data-driven smart sustainable cities represents an instance of sustainable urban development, a strategic approach to achieving the long–term goals of urban sustainability—with support of advanced Information and Communication Technology (ICT), notably the Internet of Things (IoT) and big data technologies and their novel applications. Achieving the status of data-driven smart sustianable cities of the future in turn epitomizes an instance of urban sustainability. This notion denotes a desired (normative) state in which a city retains a balance of the socio–ecological systems through adopting and executing sustainable development strategies as a desired (normative) trajectory (Bibri and Krogstie 2019a, b). This balance entails continuously improving and advancing the environmental, economic, social, and physical systems of the city over the long run—given their interdependence, synergy, and equal importance. This strategic long-term goal requires fostering linkages between scientific research, technological innovation, policy analysis, institutional practices, planning strategies, and development projects and initiatives in relevance to sustainability. It also requires a long–term vision, an interdisciplinary and trans–disciplinary approach, and a system–oriented perspective. All these requirements are at the core of the normative backcasting approach to futures studies, which facilitates and contributes to the planning, design, development, implementation, evaluation, improvement, and advancement of data-driven smart sustianable cities of the future as a new integrated model of urbanism. The focus of the futures study is on the planning, design, and development aspects of the goal-oriented backcasting process. One of the most enticing areas of research within urban sustainability is that which is concerned with normative backcasting-oriented futures studies. The relevance and rationale for adopting the normative backcasting approach to futures studies stems from the strategic planning process it entails to achieve the long-term goals of urban sustainability in the form of a vision of a desirable (sustainable) future. Backcasting is well suited to any multifaceted kind of planning process (e.g., Holmberg and Robèrt 2000), as well as to the complex problems of sustainability (e.g., Bibri 2018a, 2018c, 2019a; Carlsson-Kanyama et al. 2003; Höjer et al. 2011; Holmberg 1998; Miola 2008; Quist 2007; Robert et al. 2000).

An appropriate response to the strategic planning of data-driven smart sustainable cities should involve the analysis of several intertwined elements, including past, present, and future situations; long–term visions; the formulation, implementation, and follow–up of strategies; the execution of specific pathways, the transfer and deployment of technologies; the building and enhancement of human and social capacities; and the design of and compliance with regulatory policies. These elements cannot be isolated from one another in all kinds of urban sustainability efforts. And this is what backcasting entails as applied in the futures study, which aims to analyze, investigate, and develop a novel model for data-driven smart sustainable cities of the future. In so doing, it endeavors to amalgamate the prevailing and emerging paradigms of urbanism in terms of their strategies and solutions in order to a new model of urbanism. This amalgamation is grounded in the outcomes of four case studies, each of which investigates and compares two of a total of six cases from the ecologically and technologically leading cities in Europe: (1) Gothenburg and Helsingborg as compact cities (Bibri et al. 2020) Stockholm and Malmö as eco-cities (Bibri and Krogstie 2020a), (3) London and Barcelona as data–driven smart cities (Bibri and Krogstie 2020b), and (4) Stockholm and Barcelona as environmentally data-driven smart sustainable cities (Bibri and Krogstie 2020c).

The case study research is associated with the empirical phase of the futures study. One important use of case study approach in research is planning, which in turn is at the core of the normative backcasting approach. One of the essential requisites for employing the case study approach stems from one's motivation to illuminate complex phenomena (Merriam 2009; Stake 2006; Yin 2017). The motivation in this context is to integrate the aforementioned leading paradigms of urbanism in terms of their strategies and solutions. The resulting paradigm of urbanism is approached from the perspective of combining the strengths of sustainable cities and smart cities and harnessing their synergies in ways that primarily enable sustainable cities to improve and advance their contribution to the goals of sustainability in the face of the escalating urbanization trend.

In urban research, there are a range of qualitative approaches to data collection and analysis that researchers typically rely on to investigate a wide range of issues related to the environmental, economic, social, physical, spatial, and/or technological dimensions of the city from a wide variety of perspectives. The choice of qualitative approaches as well as their integration in this regard depends largely on what researchers intend to investigate and thus achieve as outcomes.

This paper reviews, discusses, and justifies the methodological framework applied in the futures study. In so doing, it integrates a set of principles underlying several normative backcasting approaches with descriptive case study design to devise a framework for strategic urban planning whose core objective is clarifying which city model is desired and working towards that goal.

This paper is structured as follows: Section 2 describes futures studies in terms of their characteristics, categories, and approaches. Section 3 reviews and discusses backcasting as the overarching approach applied in the futures study. Section 4 reviews and discusses the case study approach related to the empirical phase of the futures study. This paper ends, in Section 5, with concluding remarks and discussion.

Futures studies

In recent years, scientists, sociologists, futurists, and researchers within different disciplines have developed qualitative and quantitative methods for rationally predicting the future. Rationality in this context means a recognition or awareness that many different futures are possible, and that the future is far from being determined or known with absolute certainty. This is typically contingent on the kinds of decisions that people make and the kinds of actions they take in the present. Futures studies are intended to assist decision–making under uncertainty which is to be defined as indeterminacy rather than to predict the future (Dreborg 1996). Their primary purpose is to get a better understanding of future opportunities as alternatives with their differences and feasibilities. These can be employed by the aligned stakeholders as part of a given endeavor to challenge present systems, to influence or inspire the future, or to respond to the most likely future to happen. Creating a choice of futures by outlining alternatives usually form the basis for strategic planning. In light of this, futures studies help people to examine and clarify their normative scenarios of the future, to transform their visions, and to develop action plans on the basis of a wide range of techniques.

Long lasting and substantive transformations, such as sustainability transitions, can only come about through the accumulation of a number of integrated smaller–scale actions associated with successful initiatives and programs. They also operate at the interface of policy domains. Methodologies for futures studies can help to highlight these initiatives and programs and to identify such interface. Researchers employ these methodologies as an attempt to manage uncertainty by clarifying what the most desirable possibilities are, what is already known, what can be known, as well as how today's decisions may play out in each of a variety of plausible futures. The effectiveness of futures studies lies in defining a broader conceptual framework for discussing the future and in contributing to policy formulation, transition governance, and the emergence of new possibilities. And the kind of decisions futures studies seek to support under uncertainty pertains particularly to long–term decisions. In the context of the futures study, decisions are to be made in ways that reduce uncertainty about what may happen to sustainable cities in the future in the light of the escalating urbanization trend. This entails analyzing the effects of today's decisions taken in line with the vision of sustainability and supported by big data technologies in the future. The role of futures studies has become of central importance for policymaking in the sphere of urban sustainability. This process is characterized by increasing complexity at the macro–level as well as by decreasing the extent of conditionality at the micro–level due to the mounting autonomy of individual actors. This implies that social institutions are less powerful in affecting major changes through straightforward policy responses (Ling 2002).

Futures studies can be classified based on three modes of thinking about the future (Banister and Stead 2004):

- Possible futures (what might happen?). Scenario studies as descriptions of possible future states and their developments are included in this mode (Börjeson et al. 2006).
- Probable futures (what is most likely to happen?). This includes forecasting studies, which are characterized by a predictive nature and mainly focused on historical data and trend analysis.

- Preferable futures (what we would prefer to happen?). This mode is of relevance to futures studies dealing with sustainability as it focuses on desirable futures, such as backcasting and normative forecasting.

Several authors have elaborated on futures studies in relation to sustainability. Dreborg (1996) identifies four different types of futures studies in connection with sustainability, namely:

1. Directional studies which investigate different economics and other measures in the short–term that will probably work in the right direction towards sustainability.
2. Short–term studies which take immediate official goals as a starting point or a small step towards sustainability, and attempt to find means of achieving them.
3. Forecasting studies which usually apply to a long–term perspective, but restricted presumptions of the possibilities of major change make this approach fail to reach sustainability.
4. Alternative solutions and visions where the development of future (normative) scenarios as desirable futures allows them to be explored by using backcasting where the results describe a desirable future with criteria for sustainability providing the systemic framework for change.

In the framework of the futures study, the backcasting approach is prescriptive in the sense of focusing on what the data-driven smart sustainable city of the future should be. Generally, prescriptive (normative) approaches to futures studies try to aid people in clarifying their values and preferences so they can develop visions of desirable futures. Approaches to futures studies are also descriptive (extrapolative) in the sense of describing what the future will be or could be in an objective way. While many futurists strive for objectivity, most approaches to futures studies as part of qualitative inquiry rely on subjective human judgment. Nevertheless, various tools have been developed and applied to mitigate this bias through encouraging collective judgment, generating ideas to produce different judgments, and identifying discrepancies between competing views on the future, as well as substantiating consistencies and inconsistencies among and within these views (Bibri 2018c).

There could be as many approaches to futures studies as futurists because they tend to develop different ways to look ahead or to envision the future. However, according to Chatterjee and Gordon (2006), futures studies can be categorized on the basis of the context that is being studied in terms of simplicity and complexity. Specifically, if the context is predictable and largely controllable then a planning approach such as forecasting may be appropriate, and if it is unpredictable and uncertain an alternative approach such as scenario planning is more suitable (Chatterjee and Gordon 2006). Another consensual perspective among futurists is the need to employ multiple approaches to address futures problems. In the futures study, the intent is to use backcasting as a planning approach which is complemented by insights drawn from trend analysis and scenario planning methods. There is an argument that supports the idea of developing future research programs that integrate various approaches to futures studies to gain much greater insight than relying on a single approach. There are a number of different approaches to strategy analysis and future analysis that investigate what will, could, or should happen in the future that are in their application not mutually exclusive. These approaches include, but not limited to, cyclical pattern analysis, trend analysis, visioning, scenario planning, in addition to backcasting and forecasting. For a descriptive account of these approaches, which can be combined in futures studies, the interested reader can be directed to Bibri (2018c).

Researchers often need different approaches to carry out their futures studies. In this line of thinking. Höjer and Mattsson (2000) suggest that backcasting and regular forecasting are complementary rather than conflicting opposites. They add a forecasting step to the backcasting approach where forecasts and the desired vision are compared. If the vision is unlikely to be reached based on the most reliable forecasts, model calculations, and other estimates, backcasting studies should be used to generate images of the future that fulfil the targets. They also emphasize the importance of scrutinising how to attain the desirable future by working back from the desirable future to check the physical and social feasibility of the pathway towards that future. This requires not only identifying the necessary measures and actions for bringing about that future, but also using models and regular forecasting tools to quantify the consequences of different measures and actions.

In sum, there is no general consensus on a single classification of futures studies, nor a guide for the application of the most suitable approaches to futures studies. The researcher's worldview and aim are the most important criteria that determine how a futures study can be conducted and which approach should be applied to achieve its aim.

Backcasting

Backcasting in energy and sustainability studies: a brief history

The origin of backcasting dates back to the 1970s, when backcasting was proposed as an alternative planning methodology for electricity supply and demand (Robinson 1982). Robinson (1982) proposed the term "energy backcasting," assuming that future energy demand is mainly a function of current policy decisions. The futures studies concerned with energy had dealt with the so–called soft energy policy paths, characterized by the development of renewable energy technologies and a low–energy demand society (Quist and Vergragt 2006). At the time, they emerged as a response to regular energy forecasting, which was mainly based on trend extrapolation and projections of energy consumption, with a focus on large–scale fossil fuel and nuclear energy. The focus of energy backcasting was on analysis and on developing policy goals. Also, the backcasts of different alternative energy futures were meant to reveal the relative implications of different policy goals (Robinson 1982), and to determine the possibilities and opportunities for policy-making. Robinson (1990) emphasises that the purpose of backcasting is to indicate the relative feasibility and different social, environmental, and political implications of different energy futures. Recently, Anderson (2001) has adapted the energy backcasting approach, with the aim of reconciling the energy industry with sustainable development. This approach takes into account wider environmental and social responsibilities, as well as non-expert knowledge, and includes the development of supporting policies. In sum, the early focus in backcasting was on exploring and assessing energy futures and on their potential for policy analysis in the traditional sense of supporting policy and policymakers, usually adopting a government-oriented perspective.

After the widespread diffusion of sustainable development in the early 1990s, it was realized that the backcasting approach could potentially be applied to a wide range of sustainability-related subjects. Robinson (1990) marked the move towards the application of backcasting to sustainability and illustrated the interest in Sweden, as the work reported on a study supported by the Swedish energy research council. Following the strategic interest in alternative energy futures and the increasing ecological disruption in Sweden from the early 1980s onward (Mol 2000), substantial efforts were made for developing the concept of backcasting for sustainability (e.g., Dreborg 1996; Holmberg 1998; Höjer and Mattsson 2000). Backcasting for sustainability has been applied in Sweden on a range of topics, including sustainable transportation systems (Akerman and Höjer 2006; Höjer and Mattsson 2000), sustainable air transport (Åkerman 2005), GHG emissions (Höjer et al. 2011), sustainable transformation of companies (Holmberg 1998), and sustainable city design (Carlsson-Kanyama et al. 2003). A number of other studies have been conducted in other countries, especially Europe, with respect to alternative scenarios and solutions pertaining to such topics as transportation and mobility (Banister et al. 2000), sustainable technologies and sustainable system innovation (Weaver et al. 2000), sustainable household (Green and Vergragt 2002; Quist et al. 2001), and so on. For a more detailed overview of past and present applications of backcasting, the interested reader can be directed to Quist and Vergragt (2006). However, the distinctive nature of backcasting makes it appropriate for sustainability applications. Dreborg (1996) argues that, due to their normative and problem-solving character, backcasting approaches are much better suited to address long-term problems and sustainability solutions. This mainly has to do with the idea of taking desirable futures or a range of sustainable futures as a starting point for analysing their potential and feasibility, as well as the possible ways of achieving them.

In recent years, however, backcasting has become the most commonly applied approach in futures studies dealing with urban sustainability, thereby its relevance and appropriateness for data-driven smart sustainable urbanism as a form of transformative change towards sustainability. Researchers from the fields of smart cities, sustainable cities, and smart sustainable cities alike have endeavored to understand and act according to the goals of sustainability by describing visionary scenarios of a long–term future and justifying their potential attainment based on a varied set of established theories and academic disciplines and discourses in conjunction with in–depth analyses of case studies in a bid to accelerate the movement towards sustainability. This implies that a large body of research within these fields has been, and will be, formed by and founded on backcasting-oriented futures studies of different categories and on a wide variety of topics. One strand of futures studies concerns itself with the ways contemporary cities integrate the objectives and targets of sustainable development and those of smart growth in an integrated approach due to the synergetic, substantive, and disruptive effects of advanced ICT, particularly big data technologies. These effects are associated with the operational functioning, management, and planning required for future forms of urban sustainability. The evolving body of futures studies in this direction constitutes a strategic resource for understanding and unlocking the untapped potential of advanced ICT as an enabling, integrative, and constitutive set of technologies for improving and advancing sustainability.

Backcasting and strategic sustainable development: a scientific perspective

The concept of backcasting is central to the strategic approach to sustianable development. Backcasting from the system conditions of sustainability is a key concept of the Framework for Strategic Sustainable Development (FSSD) pioneered by Karl-Henrik Robèrt, founder of The Natural Step (TNS), an international nonprofit organization dedicated to applied research for sustainability in cooperation with a global academic Alliance for Strategic Sustainable Development linking universities that cooperate with industries and businesses. Backcasting from the principles of sustainability is the primary context under which the TNS Framework and the Strategic Approach to Sustainable Development (SASD) have become powerful tools for strategic planning.

Sustainable development as a strategic approach to achieving the goals of sustainability is guided by a shared understanding of the principles of sustainability that embody the end goal of sustainability. The four sustainability principles are considered as basic principles for socio–ecological sustainability as developed through scientific consensus (Holmberg and Robèrt 2000). In the sustainable society, according to Holmberg and Robèrt (2000), nature is not subject to systematically increasing …

1. … concentrations of substances extracted from the Earth's crust,
2. … concentrations of substances produced by society,
3. … degradation by physical means, and in that society …
4. people are not subject to conditions that systematically undermine their ability to meet their needs.

The purpose of articulating sustainability with scientific rigor (Clark 2007; Clark and Dickson 2003; Kates et al. 2001) is to make it more intelligible and more useful for measuring, analyzing, and managing human activities within society. A significant contribution in this line was the development of the aforementioned guiding sustainability principles. The sustainability principles should be, according to Holmberg and Robèrt (2000, p. 298):

- Based on a scientifically agreed upon view of the world
- Necessary to achieve sustainability
- Sufficient to achieve sustainability
- General to structure all societal activities relevant to sustainability
- Concrete to guide action and serve as directional aides in problem analysis
- Non–overlapping or mutually exclusive in order to enable comprehension and structured analysis of the issues.

In the framework of the futures study, sustainability principles define an end goal for urban sustainability to plan holistically in relation to urban development to ultimately achieve a balance of the socio–ecological systems in the data-driven smart sustainable city of the future. Strategic sustainable urban development is a planned development that seek to address and overcome the physical, environmental, economic, and social challenges of sustainable cities in ways that continuously enhance their performance in a rigorous, meaningful, and scientific way. This requires developing upstream solutions necessary to sustain the functioning of the city systems and making them more resilient over the long run.

Generally, the link between sustainable development and science stems from the idea that the former is an aspiration that should, as realized by several scholars over the past two decades, be achieved only on the basis of scientific knowledge. This has justified the establishment of a new branch of science due to the fact that, arguably, humanity is confronted at an ever unprecedented rate and larger scale with the ramifications of its own success as a species. The way things have changed in recent years (and the attempts being undertaken to take this into account) calls for a scientific approach to understanding the underlying web of ongoing, reciprocal relationships generating the patterns of behavior that the ecosystems are exhibiting, and to figure out the mechanisms these ecosystems are using to control themselves. The point is that the complexities, uncertainties, and hazards of the human adventures are triggering unparalleled changes increasingly requiring insights from all the sciences to tackle them if there is a shred of seriousness about the aspiration to enhance and sustain the quality of life. The real challenge emanating from the fragmented character of science lies in understanding and acting upon the causal mechanisms and behavioral patterns in response to the reciprocal relationships between different complex systems across several time and space scales. This calls for fusing disciplines, a transdisciplinary approach that reconciles and fuses the theoretical and practical knowledge, the quantitative and qualitative perspectives, and the natural and social sciences. Sustainability science is what such an integrative approach entails, and whose emphasis is on understanding changes in states rather than just their characterization. Systems theory and system analysis approaches have become the most coherent expression of this insight (Bossel 2004). Sustainability science is perhaps the most clear and desirable illustration of the endeavor of reinforcing the unified approaches and unifying tendencies in science, as well as of liberating the study of real-world processes from the boundaries between the scientific disciplines (de Vries 2013).

The quest for finding an urban development planning approach that can accommodate the wicked problems of cities, especially in relation to sustainability and urbanization, and overcome the complexity and unpredictability introduced by socio–political factors is increasingly inspiring scholars to combine urban sustainability and sustainability science under what has recently been termed "urban sustainability science." (Bibri 2019c). This term is informed by urban science, a field in which big data science and analytics is practiced, which in turn informs and sustains data–driven smart urbanism. Data-intensive science is transforming urban science and sustainability science and the way they inform urban sustainability. The objective of urban sustainability is to uphold the changing dynamics and thus reciprocal relationships (within and across levels and scales) that maintain the ability of cities to provide not just life–supporting, but also life–enhancing, conditions, exhibited by their collective behavior as complex systems.

The understanding of the city as an instance of socio–ecological systems based on sustainability science principles using a data–driven analytical approach can help address and overcome the challenges associated with the wicked problems related to urban planning and development in the context of sustainability. There is a host of new practices that sustainability science could bring to urban sustainability under the umbrella of data–intensive science, an argument that needs to be developed further and to become part of mainstream debates in urban research, practice, and policy (Bibri 2019c, 2020a). This argument is being stimulated by the ongoing discussion and development of the new ideas about the untapped potential of big data science and analytics for advancing sustainability science and urban sustainability, as well as merging them into a holistic framework informed by urban science as a field where data science can be practiced. Urban sustainability science as a research field seeks to give the broad–based and crossover approach of urban sustainability a solid scientific foundation.

Distinctive characteristics of backcasting

The term "backcasting," can denote a concept, a study, an approach, a methodology, a framework, or an interactive process among stakeholders. Therefore, it has been defined in multiple ways. Robinson (1990), p. 823 defines backcasting as a normative approach which works "backwards from a particular desired end point to the present in order to determine the feasibility of that future and what policy measures would be required to reach that point." Backcasting is a way of planning in which a successful outcome is imagined in the future, followed by the question: "what do we need to do today to reach that successful outcome?" This is more useful than forecasting, which tends to present a more limited range of options and projects the problems of today into the future. Backcasting is used in cases where it is desired to actively dictate a future outcome rather than predicting it, and also where existing trends are leading to an unfavourable state.

Backcasting is applicable in those futures studies that address the fundamental question of backcasting: "if we want to attain a certain goal, what actions must be taken to get there?" As such, it is about looking at the current situation from a future perspective. However, it is as crucially important to undertake the next steps as having lofty visions, thereby sustaining momentum by explicit shared visions of success and being able to use that to guide the next steps.

Furthermore, since backcasting deals with images of the future rather than reality, it is by definition normative, implying a certain desired view. Concerned with human societies, normativity is the phenomenon of designating some desirable or permissible actions. Researchers tend to restrict the use of the term "normative" to the evaluative sense. In consultation exercises as part of the normative–oriented visionary model of scenario construction, further insights can be gained by comparing different normative scenarios generated by different stakeholders.

Normative scenarios

In recent years, the backcasting-oriented futures studies have received more prominence in the domain of sustainability. A general purpose of futures studies is to explore possible, probable, and preferable futures by imagining the possible, assessing the probable, and deciding on the preferable. The futures study is concerned with the preferable future with respect to urban sustainability as a form of societal transition. To facilitate the understanding of the underlying logic of large-scale societal transitions towards sustainability, different types of future scenarios are often employed. Börjeson et al. (2006) categorize scenarios as explorative, predictive, or normative. Rotmans et al. (2001) classify scenarios as projective and prospective, qualitative and quantitative, participatory and expert, and descriptive and normative. The latter take values and interests into account and involve reasoning from a set of specific long–term goals that need to be achieved. The futures study applies backcasting as a normative scenario methodology to build a novel model for data-driven smart sustainable cities of the future, which can be used as a planning tool for facilitating the transition towards urban sustainability. Normative scenarios are also called desirable futures or future visions.

Furthermore, due to its goal-oriented and problem-solving nature, backcasting is especially well equipped to be applied to, or well-suited for, long-term sustainability problems (e.g., Bibri 2018c; Dreborg 1996; Holmberg 1998; Quist 2007; Robert et al. 2000). Generally, as argued by Dreborg (1996), backcasting is particularly useful when:

- The problem to be studied is complex and there is a need for major change;
- The dominant trends are part of the problem;
- The problem is a matter of externalities; and
- The scope is wide enough and time horizon is long enough to leave considerable room for deliberate and different choices and directions of development.

Many authors have justified the need for this normative scenario approach by referring to emerging disruptions in societal development (Dreborg 1996; Quist and Vergragt 2006). This is associated with, in the context of this paper, big data science and analytics and its role in improving and advancing sustainability within the framework of sustainable cities as a social organization.

Backcasting scenarios, whether based on quantitatively and qualitatively defined goals, are used to explore future uncertainties, create opportunities, build capabilities, guide policy actions, and enhance decision–making processes. As such, they allow for new options to be considered reasonable, thereby widening the perception of what could be feasible and realistic in the long-term (e.g., Dreborg 1996; Höjer and Mattsson 2000). In the framework of the futures study, they aid strategic urban actors in broadening their perspective on how sustainable cities could enhance and optimize their performance with support of big data technologies and their novel applications in the face of the escalating urbanization trend. In this respect, they describe alternative futures and develop strategies and pathways through which these futures can eventually be achieved. Hence, they are constructed from the distant future towards the present.

The backcasting process

Backcasting has attracted attention from policy-makers, organizations, and scientific communities due to its benefits for facilitating society-wide transformations. Backcasting works through envisioning and analyzing sustainable futures and then developing strategies and pathways to get there. Once the future desired conditions are imagined and articulated, the necessary steps are defined and pursued to attain those conditions. Backcasting is the process of generating a desirable future and then looking backwards to the present in order to determine the strategic actions needed to reach that specified future (Fig. 1). The first part of the process concerns the normative side of backcasting and the second part pertains to the analytical side of backcasting: both the possible ways of reaching certain futures as well as their feasibility and potential. Dreborg (1996) relates backcasting to Constructive Technology Assessment (CTA). The purpose of CTA is to broaden the technology development processes and the debate about technology with environmental and social aspects, as well as to enhance the participation of social actors. A distinction can be drawn between the analytical side and the constructive and process-oriented side of backcasting (Dreborg 1996). With respect to the analytical side, the main result of backcasting studies are alternative images of the future, thoroughly analyzed in terms of their feasibility and consequences. Concerning the constructive-oriented side, backcasting studies should provide an input to a policy developing process in which relevant actors should be involved. However, while imagining a desirable future can inspire strategies and actions, the path to success is not always obvious or straightforward. Nonetheless, the guiding images of the future tend to coalesce and together steer the trajectory of where we are headed—even if we don't arrive exactly where planned and when. This trajectory is usually based on reacting to current circumstances, expert knowledge, creativity, intuition, and common sense, but also needs to be conceivably aligned with the state of the future.

Developing pathways—course of actions, agendas, events, conditions, and triggers—in the framework of backcasting allows to imagine the impacts of future visions, which should accordingly be highly significant and require extensive improvements compared to or in relation to the current trends. In this sense, they should dovetail with the notion of urban sustainability—as a desired state of the future in which the city achieves a balance between environmental protection and integration, economic development and regeneration, social equity and stability, and physical robustness and resilience as long–term goals through the strategic process of sustainable urban development as a desired trajectory.

The normative side of backcasting—the future vision

Without first defining a future landing place, reaching urban sustainability is an unlikely outcome of any effort.The backcasting approach aids in identifying the strategies

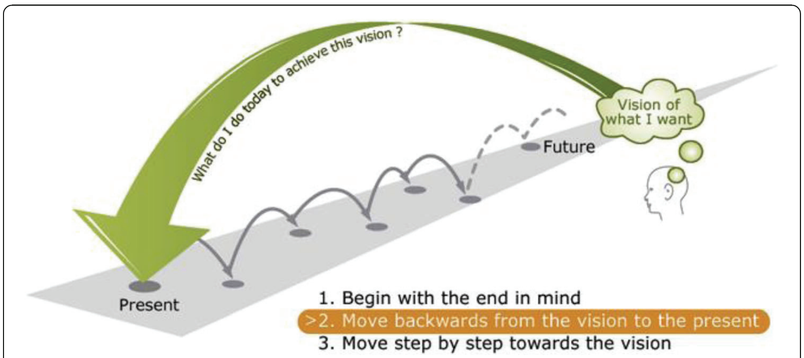

Fig. 1 The backcasting process from the Natural Step. Source: Holmberg (1998)

and pathways to be pursued to achieve the objectives and targets of sustainable development and thus the overall goal of the future vision. As a key part of the backcasting process of strategic planning, the future vision should be aligned with sustainability principles and values. As such, it depicts the city of the future as a city which retains a balance between the environmental, economic, and social dimensions of sustainability over the long run with the support of emerging and future technologies. Accordingly, the data-driven smart sustainable city is envisioned as (Bibri and Krogstie 2020c):

> *A form of human settlements that secures and upholds environmentally sound, economically viable, and socially beneficial development through the synergistic integration of the more established strategies of sustainable cities and the more innovative solutions of data-driven smart cities towards achieving the long-term goals of sustainability.*

The generation of the future vision is performed after analyzing the situation related to the current model of urbanism and the main prevailing trends and expected developments pertaining to the future model of urbanism. While some views defend that a prior evaluation grounds the vision in realism, other argue that it curtails the ability to think of "ideal states" by putting the current circumstances and capabilities at the center of attention. In the framework of the futures study, the vision of the future is based on a sequential progression--yet with sharp transformation-- into the future of the prevailing trends and expected developements and the way they intertwine with and affect one another in relation to data-driven smart sustainable cities as a holistic approach. In short, it is based on a combination of technological innovations and sustainability advancements as a co-evolutionary process.

Furthermore, the future vision is in line with the sustainable development goal 11 (SDG 11) of the United Nations' 2030 Agenda—to make cities sustainable, resilient, inclusive, and safe (United Nations 2015a). The 2030 Agenda regards ICT as a means to promote socio–economic development and protect the environment, increase resource efficiency, achieve human progress and knowledge in societies, upgrade legacy infrastructure, and retrofit industries based on sustainable design principles (UN 2015b). Therefore, the multifaceted potential of the smart city approach has been under investigation by the UN (2015c) through their study on "Big Data and the 2030 Agenda for Sustainable Development."

In view of the above, the backcasting approach entails identifying the nature and scope of the problems, issues, and challenges pertaining to sustainable cities with respect to their contribution to sustainability, and then proposing the innovative applied data-driven solutions of smart cities to develop a new paradigm of urbanism: data-driven smart sustainable cities of the future. In so doing, it sets the conditions for mitigating the extreme fragmentation of and the weak connection between sustainable cities and smart cities on the basis of the IoT and big data technologies and their novel applications.

The analytical side of backcasting—pathway-oriented category

The development of strategies and pathways to the future has long been the subject of futures studies, especially through the construction of future visions or alternative scenarios to achieve the goals of sustainability. Typically, backcasting defines criteria for a desirable future and builds a feasible and logical path between the state of the future and the present. The latter allows to set priorities, develop alternative solutions, and determine the strategic actions that need to be taken in order to reach a desirable future. This relates in this context to the backwards-lookinganalysis (Step 6) of the backcasting study, which is concerned with developing strategies and pathways to attain a single desirable future. Worth pointing out is that the backcasting approach is traditionally based on one normative vision, but multiple visions can also be used to explore different future alternatives (e.g., Tuominent et al. 2014).

There are several categories of backcasting. Wangel (2011) classifies backcasting into target-oriented backcasting (what can change); pathway-oriented backcasting (how to change); action-oriented backcasting (who could make change happen); and participation-oriented backcasting (to enhance participation and buy-in by stakeholders). The futures study is concerned with the pathway-oriented backcasting category where the focus is on how the changes can take place and the measures that support those changes. In this category, the setting of strict goals is considered less important (Vergragt and Quist 2011; Wangel 2011) compared to other categories. The pathway-oriented backcasting usually helps identify critical non-technical triggering measures. This is at the core of Step 6 of the futures study, which involves developing a series of planning measures and actions pertaining to urban design strategies, data-driven technology solutions, and sustainability targets and objectives that could be implemented in the near future. Accordingly, in the quest for the answer to how to reach the future vision, the strategies and pathways developed are intended to link the goals that may lie far ahead in the future to the decisive steps that are to be designed and taken now to achieve those goals.

Comparison of backcasting methodologies

It has been argued in the literature that conventional backcasting methodologies/approaches or some aspects of them have to be combined in futures studies. The data-driven smart sustainable city of the future integrates sustainable development, technological development, and urban planning, forming an interdisciplinary and transdisciplinary area of urbanism. This implies that a more appropriate backcasting approach as a strategic roadmap to data-driven smart sustainable urbanism as a form of transformational change should draw on insights from three relevant backcasting methodologies, namely Robinson's, TNS, and Sustainable Technology Development (STD). These are shown in Table 1 and compared in terms of their key assumptions and examples of methods.

Robinson's (1990) backcasting approach is characterized as normative and design–oriented, aimed at exploring the implications of alternative development paths as well as the underlying values. The approach gives no standard recipe for generating scenarios, but only some helpful guidelines and tools. In more detail, no reference is made to particular methods, but various groups of methods are mentioned, such as different types of scenario impact analyses, modelling, and scenario approaches. The approach does not specify who is responsible for setting the criteria and future goals and how this will be done, nor does it include stakeholder participation. It moreover focuses on technical analysis and policy recommendations. It is acknowledged that the analysis must be connected to the policy process, which can be done by involving relevant government agencies as well as the wider public. However, the futures study draw on insights from Steps 1, 2, 3, 5, and 6 in relation to sustainable urban planning.

In Sweden, backcasting has been elaborated as a methodology for strategic planning towards sustainability, which has become known as the TNS framework, It has been advocated and popularized by Karl–Henrik Robèrt, and thoroughly described by Holmberg (1998) as an approach for strategic sustainability planning in organizations that consists of four steps. Underlying this framework is the way of thinking that the future itself cannot be predicted but by viewing the physical principles of the ecosystem, a set of principles that can be set to describe the future sustainable situation. This is based on four system conditions that should be simultaneously valid in a sustainable society (Robert et al. 2000). The futures study is concerned with all four steps while taking the city as a form of social organization. This means that these steps were contextualized to be applicable to the sustainable city.

Table 1 Comparison of three backcasting methodologies and their key assumptions

Robinson's Methodology	**TNS Methodology**	**STD Methodology**
Methodological steps		
1. Determine objectives 2. Specify goals, constraints, and targets, and describe present system and specify exogenous variables 3. Describe present system and its material flows 4. Specify exogenous variables and inputs 5. Undertake scenario construction using the specified goals and constraints 6. Undertake scenario impact analysis.	1. Define a framework and criteria for sustainability 2. Describe the current situation in relation to that framework 3. Envisage a future sustainable situation 4. Find strategies for sustainability	1. Strategic problem orientation 2. Develop sustainable future vision 3. Set out alternative solutions 4. Explore options and identify bottlenecks 5. Select among options and set up action plans 6. Set up co–operation agreements 7. Implement research agenda
Key assumptions		
• Criteria for social and environmental desirability are set externally to the analysis • Goal-oriented • Policy-oriented • Design-oriented • System oriented	• Decreasing resource usage • Diminishing emissions • Safeguarding biodiversity and ecosystems • Fair and efficient usage of resources in line with the equity principle	• Sustainable future need fulfilment • Factor 20 • Time horizon of 40-50 years • Co-evolution of technology and society • Stakeholder participation • Focus on realising follow-up
Examples of methods		
• Social impact analysis • Economic impact analysis • Environmental analysis • Scenario construction approaches • System analysis and modelling • Material flow analysis and modelling	• Creativity techniques • Strategy development • Employee involvement • Employee training	• Stakeholder analysis • Stakeholder workshops • Problem analysis • External communication • Technology analysis • Construction of future visions • System design and analysis

The STD approach relates to a Dutch government program, which focuses on achieving sustainable need fulfillment in the distant future. It involves a broad stakeholder participation and the use of creativity to reach beyond existing mindsets and paradigms (Quist 2007). It has also been used for the integration of spatial functions. However, the futures study draws on Steps 1-3, which are designed to develop a long-term vision based on a strategic review of how a need might be met in the future in a sustainable way, and backwards-looking analysis is used to set out alternative solutions for sustainable need fulfilment (Weaver et al. 2000). Similarly, the 3 steps were contextualised to be applicable to data-driven technology in relation to sustainable development in the urban context. Here a data-driven smart sustainable city is a city that meets the needs of its present citizens without compromising the ability for other people or future generations to meet their needs, and where advanced ICT, notably big data technology support its endeavor to not exceed local or planetary environmental limits.

Based on the three above backcasting approaches, the key assumptions underlying the backcasting approach applied in the futures study—considering its overall aim—include:

- Decreasing energy usage
- Efficient utilization of resources in line with the equity principle
- Mitigating pollution
- Sustainable future fulfilment of needs
- Safeguarding biodiversity and ecosystem
- Criteria for social and environmental desirability set externally to the analysis
- Goal-oriented
- Policy-oriented
- Design-oriented
- System-oriented
- Time horizon of 25–50 years
- Co-ev.olution of technology and society

The guiding questions for the six steps in the backcasting-oriented futures study

The literature shows that there are a number of backcasting approaches and methodologies applied in futures studies. While these differ in their steps and thus guiding questions, they tend to share the essentials. The backcasting framework is adaptive in nature based on the specific context under which it is applied, e.g., research projects with different aims, purposes, scopes, complexities, and time horizons, just to name a few. The result is a process that can be considered more as a set of guiding principles, tools, and practices to achieve a certain goal than as a strict adherence to the application of a rigorous method encompassing all the steps involved in a given backcasting methodology. Unlike methodology, a framework is a loose but incomplete structure which leaves room for other practices and tools to be included, but provides much of the process required. Also, the terms “backcasting methodology” and “backcasting approach” are differentiated in the literature. Quist (2007) clearly elaborates that the backcasting methodology should be applied in such concrete cases, whereas the backcasting approach should be used to describe general and more abstract terms. Fundamentally, a backcasting approach involves four steps, namely (Höjer and Mattsson 2000):

- The setting of a few long-term targets
- The evaluation of each target against the current situation, prevailing trends, and expected developments
- The generation of images of the future that fulfill the targets
- The analysis of images of the future in terms of feasibility, potential, and pathways towards images of the future (Akerman and Höjer 2006).

Different backcasting approaches are emerging in the field of urban sustainability as to its various domains (e.g., transport, mobility, energy, environment, design, and technology). In this light, Bibri (2018c) synthesizes a backcasting approach to smart sustainable city development based on the review of a number of futures studies using different backcasting approaches and methodologiesn, and later, Bibri (2020a) tailored it to the futures study with respect to the requirements of the future vision (Table 2).

The time horizon in backcasting-oriented futures studies

A typical time horizon used in many backcasting-oriented futures studies is 50 years. This time horizon is appealing because it is both realistic and far enough away to allow major changes and even disruptions in technologies and cultural norms and values. There also is a large body of work on backcasting that takes the perspective of 25-50 years as a time horizon. The futures study follows this perspective by covering the time period from 2020 to 2050, the time reasonably needed to develop the data-driven smart sustainable city as a desirable future. The rationale for this is that this new model of urbanism concerns particularly, but not only, those cities that are badging or regenerating themselves as sustainable, where, for example, some sustainable energy and waste systems, dense and diverse urban patterns, sustainable transportation infrastructure, green areas and parks, and technological infrastructure are already in place. And as they move towards 2050, a set of strategic pathways will be taken along the way to reach the optimal level of sustainability with the support of emerging and future ICT. And what this entails in terms of developing and implementing the IoT and big data technologies and their novel applications as well as establishing the associated technical and institutional competences on a citywide scale. Nonetheless, the futures study is not setting out a fixed time frame as the future is unknown and the world is uncertain, and the implication of this is that it can still take longer for sustainable cities to get closer to or reach the final destination. Not to mention those cities that are in the process of regenerating themselves as, or manifestly planning to become, sustainable and then smart sustainable. Worth pointing out is that the time horizon of 25-50 years associated with future visions as an evolutionary process is a basic principle to allow the policy and planning actions to pursue the path towards a more sustainable future.

Envisioning and attaining a transformational change which substantiates, extends, and also challenges the existing assumptions and claims made on sustainable cities as a problem of significant complexity, with a long time horizon to allow for making determined choices, is what backcasting entails as a strategic planning process and a problem-solving framework. In this regard, we identify signals of sustainable change

Table 2 The guiding questions for each step in the backcasting-oriented futures study

The guiding questions for the backcasting study	Methods and tools
Step 1: Detail strategic problem orientation (Part 1) 1. What is the model of urbanism to be studied? 2. What are the aim, purpose, and objectives of the backcasting study in relation to this model? 3. What are the long–term targets declared by the goal–oriented backcasting approach? 4. What are the objectives that these targets are translated to for backcasting analysis?	Research design and problem formulation
Step 2: Detail strategic problem orientation (Part 2) 1. What are the main prevailing trends and expected developments related to the model to be studied? 2. What are the key sustainability problems associated with the current model of urbanism and what are the causes? 3. How is the problem defined?	Trend analysis and problem analysis
Step 3: Generate a sustainable future vision 1. What are the demands for the future vision? 2. How does the future model of urbanism look like? 3. How is the future model of urbanism different from the current model of urbanism? 4. What is the rationale for developing the future model of urbanism? 5. Which sustainability problems have been solved and which technologies have been used in the future vision?	Creativity method and visualization method
Step 4: Conduct empirical research 1. What is the rationale for the methodological framework to be adopted? 2. Which category of case study design is most relevant to investigating the dimensions of the future model of urbanism? 3. How many case studies are to be carried out and what kind of urban phenomena should they illuminate? 4. To what extent can this investigation generate new ideas and illustrate the theories applied and their effects, as well as underpin and increase the feasibility of the future model of urbanism?	Case study method
Step 5: Specify and integrate the components of the future model of urbanism 1. What urban and technological components are necessary for developing the future model of urbanism? 2. How can all these components be integrated into a framework for strategic sustainable urban development planning? 3. What are the benefits, potentials, and opportunities of the future model of urbanism?	Creativity method
Step 6: Perform backwards–looking analyses 1. What built infrastructure changes are necessary for achieving the future vision? 2. What urban infrastructure changes are necessary? 3. What ICT infrastructure changes are necessary? 4. What social infrastructure changes are necessary? 5. What institutional changes are necessary?	Backcasting analysis

Source: Bibri (2020a)

and also determine short–term planning and policy goals that can facilitate the long–term outcomes of the needed transition towards sustainability. Backcasting is most relevant when the future is uncertain and our actions are likely to influence, inspire, or, ideally, create that future. Given that there is often greater uncertainty over what may happen in longer time frames, the future vision may usefully be described using principles and well–designed goals rather than specifics.

Case study research

Case study research has long had a prominent position in many disciplines and professional fields, established as a credible, valid design that facilitates the investigation and understanding of complex phenomena in their real-world settings. It has benefited from the prior development of the theoretical propositions contributed by a number of researchers with different backgrounds to this design. Similarly, the methodological development of case study research has emanated from the influence of the different researchers' perspectives and interpretations of this design. This has resulted in a pragmatic, flexible research approach, capable of providing an up-close, in-depth, and detailed examination of a wide range of specific cases and a comprehensive understanding of a large number and variety of issues. Therefore, case study research has grown in reputation as an effective research methodology. As a result, it has undergone substantial improvement through the application of a diversity of approaches. Central to this is the underpinning ontological and epistemological orientations of the numerous researchers involved in the evolution of case study research as coming from various disciplines. While over time the contributions of those researchers have helped to develop and strengthen case study research, the variety of disciplinary backgrounds has also added complexity, particularly around how such research is defined, described, and applied in practice. The nature of this complexity is explored in more detail by Farquhar (2012).

Definitional issues

There is a variety of definitions and descriptions of case study research presented across the literature, which has resulted from researchers with different philosophical perspectives. The proliferation of definitions can create confusion when attempting to understand case study research. The most common definitions come from the work of Yin (2014), Stake (1995), Merriam (2009), Thomas (2011), and Creswell et al. (2007). Yin's definition (2014) focuses on the scope, process, and methodological characteristics of case study research, emphasizing the nature of inquiry as being empirical, and the importance of context to the case. On the other hand, Stake (1995, p. xi) maintains a focus on what is studied (the case) rather than how it is studied (the method), describing case study research as "the study of the particularity and complexity of a single case, coming to understand its activity within important circumstances." Merriam (2009, p. 40) includes what is studied (the case) and the products of the research (the outcome) when defining case study as: "an in depth description and analysis of a bounded system". The author emphasizes the defining feature of case study research as being the object of the study (the bounded system; i.e., the case) adding that case study research focuses on a particular thing and that the product of an investigation should be descriptive and heuristic in nature. In taking the distinction between the subject of the study and the object of the study into account, Thomas (2011, p. 513) defines cases studies as "analyses of persons, events, decisions, periods, projects, policies, institutions, or other systems that are studied holistically by one or more methods. The case that is the subject of the inquiry will be an instance of a class of phenomena that pro-vides an analytical frame—an object—within which the study is conducted and which the case illuminates and explicates." Creswell et al. (2007) describe case study as a type of design in qualitative research, an object of study, and a product of the inquiry. The authors conclude with a definition that collates the hallmarks of the key approaches to case study and represents the core features of a case study: "a qualitative approach in which the investigator explores a bounded system (a case) … over time through detailed, in–depth data collection involving multiple sources of information … and reports a case description and case–based themes" (Creswell et al. 2007, p. 245). In particular, the case study approach entails the use of multiple sources of evidence. The use of multiple methods to collect and analyze data are found to be mutually informative in the case study research where together they provide a more synergistic and comprehensive view of the problem under study (Flyvbjerg 2011; Merriam 2009; Stake 2006). All in all, the varied definitions stem from the researchers' differing approaches to developing case study methodology and often reflect the elements they emphasize as central to their designs. The diversity of the approaches to case study, which is addressed next, subsequently adds diversity to its definition and description (Flyvbjerg 2011).

In the framework of the futures study, the four case studies analyze a range of different elements within the boundaries of four cities and two districts. They examine contemporary real-world phenomena and seek to inform the theory and practice of data-driven smart sustainable cities of the future by illustrating what has worked well, what has been achieved, what is the current situation, what needs to be improved and transformed in the future, and how this can be done. They serve as a way to illustrate theories and the effects of their application in regard to urban living. They are additionally regarded useful for understanding how different elements fit together and (co-)produce the observed impacts in a particular context based on a given set of intertwined factors.

The mixed use of terminology—methodology versus method

One of the challenges to the understanding of case study research pertains to it being referred to as a methodology and a method. Mills (2014) distinguishes methodology as the lens through which the researcher views and makes the decision about the study, and method as a set of procedures and techniques employed in the study. Also, both quantitative and qualitative methods are used within the case study designs, which brings further obscurity to the question of methodology (Stake 1995; Stewart 2014; Yin 2014). Compounding this ambiguity is the terminology used in the literature, an approach, research design, qualitative design, research strategy, case study, qualitative case study, and/or a form of inquiry (e.g., Anthony and Jack 2009; Brown 2008; Creswell 2014; Merriam 2009; Simons 2009; Stake 1995; 2006; Stewart 2014; Yin 2014, 2017). These terms are used interchangeably without definitional clarity (see, e.g., Creswell 2014; Flyvbjerg 2011; Merriam 2009; Stake 1995, Stake 2006; Simons 2009; Stewart 2014; Yin 2014, 2017) This mixed use of terminology has generated a cacophony that has led to an exasperating confusion in case study research. This is due to the definitional separations between these terms, especially methodology and method, and the varied application of the case study in research endeavors (George and Bennett 2005). Therefore, the distinction between methodology and method accentuates the need for the researcher to describe the particular underpinning methodology adopted and to clarify the alignment of the chosen methods used with their philosophical assumptions and their chosen approach. In the context of the futures study, case study research emphasizes that an overarching methodology shapes a case study design and that multiple sources of data and methods are used (Merriam 2009; Stake 2006; Yin 2014).

Design. purpose, and process

Various designs have been proposed for preparing, planning, and conducting case study research. The philosophical underpinnings of the researchers that have contributed to the development of case study research have created a variety and diversity of approaches. Under the more generalized category of case study, there exist several categories, each of which is custom selected for use depending on the objectives of the researcher, including:

- *Illustrative case studies*—these are primarily descriptive studies. They typically utilize one or two instances of an event to show the existing situation. Illustrative case studies serve primarily to make the unfamiliar familiar and to give readers a common language about the topic in question
- *Exploratory case studies*—these are condensed case studies performed before implementing a large scale investigation. Their basic function is to help identify questions and select types of measurement prior to the main investigation. The primary pitfall of this type of study is that initial findings may seem convincing enough to be released prematurely as conclusions.
- *Cumulative case studies*—these serve to aggregate information from several sites collected at different times. The idea behind these studies is that the collection of past studies will allow for greater generalization without additional cost or time being expended on new, possibly repetitive studies.
- *Critical instance case studies*—these examine one or more sites either for the purpose of examining a situation of unique interest with little to no interest in generalization, or to call into question a highly generalized or universal assertion. This method is useful for answering cause and effect questions.

The methodological discourse stresses a number of themes on the direction and organization of case studies—their design. Thomas (2011) summarizes some of the better-known analyses in Table 3.

For an explication of the general themes raised in Table 3, the interested reader can be directed to the analysis from George and Bennett (2005). This especially useful analysis draws heavily on the widely used typologies of Lijphart (1971) and, principally, Eckstein (1975). George and Bennett (2005) emerge with six types of case study, namely:

1. *Atheoretical (or configurative idiographic) case studies*—the goal is to describe a case very well, but not to contribute to a theory;
2. *Interpretative (or disciplined configurative) case studies*—the goal is to use established theories to explain a specific case;
3. *Hypothesis-generating (or heuristic) case studies*—the goal is to inductively identify new variables, hypotheses, causal mechanisms, and causal paths. Outlier cases may be especially valuable;

4. *Theory testing case studies*—the goal is to assess the validity and scope conditions of single or competing theories;
5. *Plausibility probes preliminary studies—t*he goal is to assess the plausibility of new hypotheses and theories, or to determine whether further study is warranted; and
6. *Building block studies of particular types or subtypes of a phenomenon*—the goal is to identify common patterns across cases or serve a particular kind of heuristic purpose

Notwithstanding the commonalities and differences of these types of case studies, the key feature emerged from this list is that there is a mixture of criteria for classification. However, while case study research has evolved to be a pragmatic, flexible research approach, the variation in application, validity, and purposefulness can create a confusing platform for its use (Anthony and Jack 2009). Nevertheless, the versatility of case study research to accommodate the researcher's philosophical position presents a unique platform for a range of studies that can generate greater insights into different areas of inquiry. With the capacity to tailor approaches, case study designs can address a wide range of questions that ask why, what, and how of an issue and assist researchers to explore, explain, describe, evaluate, and theorize about complex issues in context. This relates to the decisions that need to be made about the purpose, approach, and process in the case study. Thomas (2011) proposes a typology for the case study wherein purposes are first identified (evaluative, exploratory, or descriptive), then approaches are delineated (theory-testing, theory-building, or illustrative), then processes are decided upon, with a principal choice being between whether the study is to be single or multiple, and choices also about whether the study is to be retrospective, snapshot, or diachronic, and whether it is nested, parallel, or sequential.

Following this typology, the purpose in the four case studies is *descriptive*, the approach is *illustrative*, and the process is *multiple*. The purpose is about the reason of doing these studies. The approach is about the broad objects of these studies. The process is bout the operational processes of these studies, which entails returning to the six subjects (as distinct from the four objects) and to the boundary decisions made at the outset. There has to be an examination of the nature of the decisions that were made at that time about the parameters that delimit the subject of the study (Thomas 2011). In this context, these parameters fall around the locus of defining the four cases by more of a range of boundary considerations: a range of different elements that were studied in their complexity. This

Table 3 Kinds of case studies as enumerated by different analysts

Meriam (1988)	Stake (1995)	Bassy (1999)	de Vaus (2001)	Yin (2009)
Descriptive	Intrinsic	Theory seeking	Descriptive/explanatory	Critical
Interpretative	Instrumental	Theory testing	Theory testing/building	Extreme/unique
Evaluative	Single/collective	Storytelling	Single/multiple case	Longitudinal
—	—	Picture drawing	Holistic/embedded	Representative
—	—	Evaluative	Parallel/sequential	Revelatory
—		—	Retrospective/prospective	—

Source: Adapted from Thomas (2011)

determines the process of the four case studies, and this is about the presence of the comparative element to these studies as multiple ones (Stake 2005). As stated in this regard by Thomas (2011, p.): “the case study, while it is of the singular, may contain more than one element in its subject and if this is so—that is, if there are two or several cases—each individual case is less important in itself than the comparison that each offers with the others.” The key focus in the four case studies is not on the nature and shape of relationships per se in one city but rather on, to some extent, the nature of the difference between the one and the other and what this informs us about the dynamics that are significant in this difference. This comparative element is why Schwandt (2001) calls this kind of case study cross-case analysis. For the four case studies, we considered additional features of the situation. How could the different studies be used for comparison—for cross-case analysis in Schwandt’s (2001) terms? The principal means of doing this was by straightforward comparison between clearly different examples. Moreover, the four studies were parallel in the sense that the two cases in each of them were happening and studied concurrently.

To elaborate further on the purpose, descriptive case study accentuates the flexibility of case study research as a distinct form of inquiry that enables detailed and in-depth insights into a diverse range of issues across a number of disciplines. There is a consensus that the focus of a case study is the detailed inquiry of a unit of analysis as a bounded system (the case), over time, within its context. In descriptive case study research, questions and propositions about the four phenomena of compact cities, eco-cities, data-driven smart cities, and environmentally data-driven smart sustainable cities are carefully scrutinized and articulated at the outset. The articulation of what is known about these phenomena is referred to as a descriptive theory. Therefore, the main purpose of the four case studies is to describe the selected cases in detail and in depth based on that articulation, and in their real–world settings. It is worth pointing out that internal validity in research design is not relevant as in most descriptive studies. Internal validity denotes the approximate truth about inferences regarding cause-effect, or the extent to which a study establishes a trustworthy cause-and-effect relationship between a treatment and an outcome. Accordingly, it is relevant in studies that attempt to establish a causal relationship such as explanatory and hypothesis-generating (or heuristic) case studies, whereas descriptive research is used to describe some characteristics of certain phenomena, and does not address questions about why and when these characteristics occurred—no causal relationship.

Descriptive case study steps

Descriptive case study research, as defined by (Yin 1984, 2009), has been identified as the most suitable methodology for the four case studies. This methodology has been chosen considering the nature of the problems being investigated, the research aim, and the present state of knowledge with respect to the topics on focus. It involves the description, analysis, and interpretation of the present nature, composition, and processes of the six cities selected, where the focus is on the prevailing conditions. That is, how these cities behave in terms of what has been realized and the ongoing implementation of plans based on the corresponding practices and strategies depending on the topic of each of the four case studies. To obtain a broad and detailed form of knowledge in this regard, we adopted a process that consists of five steps tailored to each of the four case studies conducted (see Table 4):

Based on Table 4, the outcomes of descriptive case study can lead to an in-depth understanding of such aspects as behaviors, processes, practices, and relationships in context with respect to different phenomena.

Selection criteria

There are different strategics for selecting the cases to be investigated. Seawright and Gerring (2014) list seven case selection strategies:

1. *Typical cases*—exemplify a stable cross-case relationship. These cases are representative of the larger population of cases, and the purpose of the study is to look *within* the case rather than compare it with other cases
2. *Diverse cases*—have variation on the relevant X and Y variables. Due to the range of variation on the relevant variables, these cases are representative of the full population of cases.
3. *Extreme cases*—have an extreme value on the X or Y variable relative to other cases
4. *Deviant cases*—defy existing theories and common sense. They not only have extreme values on X or Y (like extreme cases), but defy existing knowledge about causal relations
5. *Influential cases*—are central to a model or theory
6. *Most similar cases*—are similar on all the independent variables, except the one of interest to the researcher
7. *Most different cases*—are different on all the independent variables, except the one of interest to the researcher

The strategy pursued in the four case studies is *influential cases***.** In addition, the selection of the six cases investigated was done in line with the overall aim of the futures study, with a focus on the leading cities from the ecologically and technologically advanced European countries with respect to urban planning and development. The subjects have come into focus because of the inherent interest of the six cases—they are key cases of the phenomena of compact cities, ecological cities, data-driven smart cities, and environmentally data-driven smart sustainable cities.

However, the subjects identified are in no sense a sample, representative of a wider population. Rather, they are selected because they are interesting examples through which the lineaments of the four objects: (1) compact urbanism, (2) ecological urbanism, (3) data-driven smart urbanism, (4) and environmentally data-driven smart sustainable urbanism can be refracted. Their scope is not restricted (e.g., Thomas 2011; White 1992).

Compact cities: Gothenburg and Helsingborg

The cases of Gothenburg and Helsingborg have been selected using a theoretical sampling approach (Yin 1984). The two cities fall within the category of large cities in Sweden:

Table 4 Descriptive case study steps for the four case studies conducted

Compact City
• Using a narrative framework that focuses on the compact city model and its contribution to the three goals of sustainability as a real–world problem and that provides essential facts about it, including relevant background information • Introducing the reader to key concepts, strategies, practices, and policies relevant to the problem under investigation • Discussing benefits, conflicts, and contentions relevant to the problem under investigation • Explaining the actual solutions in terms of plans, the processes of implementing them, and the expected outcomes. • Offering an analysis and evaluation of the chosen solutions and related issues, including strengths, weaknesses, tradeoffs, and lessons learned.
Eco-City
• Using a narrative framework that focuses on the eco-city as a real-world problem and provides essential facts about it, including relevant background information • Introducing the reader to key concepts, models, and design strategies relevant to the problem under investigation • Discussing benefits and research gaps and issues relevant to the problem under investigation • Explaining the actual solutions in terms of plans, the processes of implementing them, and the expected outcomes • Offering an analysis and evaluation of the chosen solutions and related issues, including strengths, weaknesses, tradeoffs, and lessons learned.
Data-Driven Smart City
• Using a narrative framework that focuses on the data-driven smart city as a real–world problem and provides essential facts about it, including relevant background information • Introducing the reader to key concepts, technologies, and data-driven smart sustainable urbanism processes and practices relevant to the problem under investigation • Providing an overview of the literature review previously conducted in relation to the study, which delivers a comprehensive, state–of–the–art review on the sustainability and unsustainability of smart cities in relation to big data technology, analytics, and application in terms of the underlying foundations and assumptions, research problems and debates, opportunities and benefits, technological developments, emerging trends, future practices, and challenges and open issues • Explaining the actual solutions in terms of plans, the processes of implementing them, and the expected outcomes • Offering an analysis and evaluation of the chosen solutions and related issues, including strengths, weaknesses, tradeoffs, and lessons learned.
Environmentally Data-Driven Smart Sustainable City
• Using a narrative framework that focuses on data-driven smart solutions and their role and potential in improving and advancing environmental sustainability in the framework of the smart sustainable city as a real–world problem, and provides essential facts about it, including relevant background information. • Introducing the reader to key concepts, core enabling technologies, infrastructures, landscapes, frameworks, as well as urban operating systems and urban operations centers, all with relevance to the problem under study. • Identifying the commonalities and differences between the two cities with respect to the emerging technologies • Explaining the actual solutions in terms of plans and visions, the processes of implementing them, and the realized and expected outcomes • Offering an analysis and evaluation of the relevant solutions and related issues, including strengths, weaknesses, and lessons learned.

Gothenburg is the second-largest city in Sweden, after the capital Stockholm, fifth-largest in the Nordic countries. It is located by Kattegat, on the West coast and in the south-west of Sweden. The area of Gothenburg has an approximate size of 447.8 km^2. Gothenburg has a population of approximately 599,000 in the city center and about 1 million inhabitants in the metropolitan area. It is home to many students from all over the world, as there are two universities in the city: the University of Gothenburg and Chalmers University of Technology. It is in a phase of expansion with a growing population and as a result of increased immigration. The crisis during the 1970s has drastically transformed Gothenburg, from an industrial city to a knowledge and event city, where the two universities have become very important, and the focus on the sustainable development has increased.

Helsingborg is located in the Öresund region, exactly where the Øresund straits are narrowest. The area of Helsingborg has an approximate size of 346 km^2, Around 3.9 million people live and work in this region. Approximately 135,300 people live in Helsingborg. Thanks to its position, Helsingborg is a strategic hub, close to Malmö and Copenhagen. It is a regional center situated within the larger metropolitan regions of Malmö and Copenhagen. It is a former industrial city that has made an effort to regenerate old industrial sites in response to the need for enhanced economic growth in order to contribute to new commercial and cultural activities and to create new urban residential areas while keeping its industrial heritage intact.

In addition, the ambition and success of these cities in the field of compact urbanism makes their planning practices and development strategies an ideal sample to analyze. This assertion can be demonstrated considering the international positioning of Sweden in urban sustainability. Sweden is one of the leading Scandinavian, European, and Global countries that have exemplary practical initiatives in sustainable cities, both compact cities and eco–cities, in addition to a number of recent endeavors related to smart sustainable cities. According to several rankings, Sweden, Denmark, Finland, Norway, Germany, the Netherlands, and Japan have the highest level of sustainable development practices (Dryzek 2005). Another ranking has recently been reported based on 2018 Environment Performance Index (EPI) data: Sweden is one of the world's leading countries in sustainability and has an overall score of 80.51 in regard to environmental friendliness (Buder 2019). In fact, several empirical studies identify from the mid–1980s onward an increasing ecological disruption in most of the ecologically advanced nations, such as Sweden, Denmark, Germany, and the Netherlands (Mol 2000). Sweden and the rest of the Nordic countries have a comparatively low impact in terms of CO2 emissions (The Norden 2008).

The two cities selected have been receptive to the compact city ideal. They have chosen the compact city model as the most effective planning system that can go hand in hand with sustainable development in light of the relevance and usefulness of the findings produced by many studies in the field of sustainable urbanism. As such, they may be seen as successful examples of compact city planning and development, and critical cases in sustainable urban development. This is due to their long planning traditions and the existence of relatively solid economic resources on the local level, the national focus on sustainability in Sweden, and the wide authorization given to the local authorities (Baldersheim and Ståhlberg 2002; Kalbro et al. 2010; Rose and Ståhlberg 2005). Moreover, they express sustainability ambitions in their master and comprehensive plans, support progress and expansion over time, and experience developmental pressure on their landscapes due to rapid urban growth. Additionally, it was important to ensure that there was sufficient information available in the public realm to carry out the analysis of the two cases. All in all, the selection criteria secured cases where sustainability discourses, planning measures, practical advances, and future goals are present. Gothenburg and Helsingborg illustrate how ambitious cities handle the challenges of sustainability and urbanization, and how different values and interests are weighted and secured through urban planning and development.

Eco-cities: Stockholm and Malmö

The cases of Stockholm and Malmö and Helsingborg have been selected using a theoretical sampling approach (Yin 1984). The two cities fall within the category of large cities in Sweden:

Centrally located in the growing Baltic region, Stockholm is the largest city in Sweden, the capital of Sweden, and the most populous urban area in Scandinavia. Approximately 1.633 million habitants live in the urban area, 2.4 million in the metropolitan area, and 965,232 in the municipality. Moreover, Stockholm is an important global city and one of the world's cleanest capitals and metropolises due to the absence of heavy industry and fossil fuel power plants. Indeed, it has a long history of environmental work and was the first city to be granted the European Union's Green Capital award by the European Commission in 2010 due to its high environmental standards and ambitious goals for further environmental improvement (European Green Capital 2009). This includes climate change, air quality, green energy, waste and water management, wastewater treatment, sustainable land use, environmental management, and sustainable transport. The city has a long-term commitment to sustainable development and the environment. Stockholm and SRS received an award for best sustainable urban development project in the category Sustainable Communities, which was presented at the UN Climate Change Conference in Paris 2015 by the C40 Cities Climate Leadership Group, a network connecting more than 80 of the world's megacities (Stockholm City 2020). The award is proof that Stockholm is an international leader in sustainable urban development.

Malmö is the largest city of the Swedish County of Skåne and the third-largest city in Sweden, after Stockholm and Gothenburg, with a population of 316,588 inhabitants out of a municipal total of 338,230 in 2018. Being perfectly situated along the straights, it separates Sweden from Denmark, and also connects Sweden to Denmark through the Öresund bridge, whose opening in 2000 made Malmö Sweden's principal point of entry. Since the construction of the Öresund Bridge, Malmö has undergone a major transformation which can be seen more clearly in Western Harbor (Västra Hamnen) than in any other part of Malmö. The Municipality of Malmö had initially invested in residential development on the site by means of a European housing exhibition focused on sustainability—Bo01, exploring a drastic vision of future living intended to provoke discussion and to be a best practice exemplar pilot project for a mixed district. This event was held in Malmö in 2001.

Another rationale for selecting these cities is that, in addition to what Sweden is renowned for as mentioned earlier, they have long been receptive to the eco-city ideal as well as engaged in ecological planning for almost two decades (Bibri and Krogstie 2020a). Malmö is the second largest city in Sweden's fastest growing urban landscapes after Stockholm and one of the Sweden's most ambitious cities in terms of sustainable planning. This is well demonstrated by the great deal of planning material and ideas produced about sustainable cities, for which the city has indeed been internationally acclaimed and awarded as notably:

- The Liveable community's award 2007
- Sweden's first Fairtrade City 2006 and 2012
- The fourth greenest city in the world by Grist in 2007
- One of the first creative city in Europe by Fast Company 2009

- The World Green Building Council's BEX Award 2009
- Sweden's most climate-smart Municipality 2011
- Environment Municipality of the Year 2010, 2013, and 2014
- European Green Capital Finalist 2012 and 2013
- Top 3 greenest cities in the world 2013
- The fourth Sustainable Urban Mobility Planning (SUMP) Award 2015

The two cities have chosen the eco-city strategy as the most effective planning system that can go hand in hand with sustainable development in light of the relevance and usefulness of the findings produced by many studies in the field of ecological urbanism. Particularly, Stockholm Royal Seaport (SRS) and Western Harbor in Malmö have been selected as eco-city districts for investigation. In recent years, much of the environmental work within Stockholm has focused on developing new sustainable urban districts. One recent initiative is the SRS district, whose vision is to become a "world class environmental city district" (Stockholm City 2010). SRS is an area of 236 ha that is being transformed from a brownfield zone into a site of 12,000 homes, 35,000 workplaces, 600,000 m2 of commercial spaces, and parks and green spaces, with approximately 35,000 people to live and/or work in the area. It is designated as an environmental profile area with the mandate to become a model of sustainable urban development (Stockholm City 2020). It is among the key climate-positive projects in the world that are considered as examples of successful environmental and economic urban developments, demonstrating that cities can reduce carbon emissions and grow in climate friendly ways. The vision of SRS relates to the overall goal established by the City of Stockholm to be fossil fuel–free by 2050 (Stockholm City 2009, 2018). In this respect, SRS environmental profile should consolidate Stockholm's position as a leading capital in climate work, support the marketing of Swedish environmental technology, and contribute to the development of new technologies (Bibri 2020a, b).

With respect to Western Harbor, it is designated as an environmental profile area with the mandate to become a model of modern eco-city district. Its aim is to become an international leading example of an environmentally sound, densely populated district. Bo01 represents the first step in the process of transforming the 160 ha of Western Harbor area into a sustainable urban district. When completed, the Western Harbor area will consist of a total of approximately 11,000 homes and 17,000 jobs, and over 20,000 people will be able to live in the area (Malmö City 2015). At the beginning of 2014, this district had approximately 4000 homes and approximately 10,000 jobs, in addition to a number of facilities and services (Malmö City 2015). The original plan created to redevelop this formerly industrial, waterfront real estate has led to the transformation of 18 ha into a mixed-use residential community built according to sustainable principles. The development of Bo01 in 2001 was to accommodate commercial and social uses, and related housing exhibition in 2002 showcased what was achievable in terms of planning, designing, and building to the highest energy efficiency and renewable energy standards. This in turn enabled the testing of new sustainable technologies and approaches to their application on a wider scale. However, the key goal of Western Harbor is to become an environmentally sound and sustainable urban district, integrating all three dimensions of sustainability, ecological, economic, and social (Malmö City 2015).

SRS and Western Harbor illustrate how ambitious districts handle the environmental and sustainability challenges, and how different values and interests are weighted and secured through urban planning and development. As such, they may be seen as successful examples of ecological urbanism, as well as critical cases in sustainable urban development. Moreover, Stockholm and Malmö express environmental and sustainability ambitions in their master and comprehensive plans, support progress and expansion over time, and experience developmental pressure on their landscapes due to urbanization (Bibri and Krogstie 2020a).

Data-driven smart cities: Barcelona and London

The cases of Barcelona and London have been selected using a theoretical sampling approach (Yin 1984). The two cities fall within the category of large cities in Europe:

Barcelona is located in the northeast of Spain on the Mediterranean coast. It is the capital and largest city of the autonomous community of Catalonia, as well as the second most populous municipality of Spain. The area of Barcelona has an approximate size of 101.9 km^2 and a population of 5.586 million habitants. With a population of 1.6 million within city limits, its urban area extends to numerous neighboring municipalities within the Province of Barcelona and is home to around 4.8 million people, making it the fifth most populous urban area in the European Union after Paris, the Ruhr area, Madrid, and Milan. It is one of the largest metropolises on the Mediterranean Sea, located on the coast between the mouths of the rivers Llobregat and Besòs, and bounded to the west.

London is the capital and largest city of England and the United Kingdom. The city stands on the River Thames in the south-east of England, at the head of its 50-mile (80 km) estuary leading to the North Sea. The area of London has an approximate size of 1572 km^2 and a population of 8.982 million habitants. London is considered to be one of the world's most important global cities. London's universities form the largest concentration of higher education institutes in Europe, and London is home to highly ranked institutions.

Selecting Barcelona and London amongst all the top cities leading the smart city ranking (e.g., Eden Strategy Institute 2018) and the data-driven city ranking (Bibri and Krogstie 2020b; Nikitin et al. 2016) in the world is justified by three key reasons. First, the focus of the futures study is on the European Cities of which London and Barcelona are the leading data-driven smart cities. Second, both cities are widely recognized and mostly reputed for using applied data-driven technology solutions in their operational functioning and planning as part of the city management, and what this entails in terms of infrastructure, competencies, data sources, and data-oriented institutional competences (e.g., Bibri 2020a; Batty 2013; Eden Strategy Institute 2018; Kitchin 2014; Kitchin 2016; Nikitin et al. 2016; Noori et al. 2020; Sinaeepourfard et al. 2016). Third, they are increasingly seen as the leading European cities that are taking the initiative to use and apply the IoT and big data technologies to advance sustainability—thereby evolving into what has been termed as data-driven sustainable smart cities. The local governments of Barcelona and London have established a number of projects and implemented several planning measures for modernizing their ICT infrastructure and strengthening their readiness to integrate data-driven technology solutions into urban processes and practices.

In view of the above, the two cities demonstrate exemplary practical initiatives as regards the integration of data-driven solutions and sustainable development strategies. As such, they may be seen as successful examples of the emerging paradigm of smart urbanism, as well as critical cases in sustainable development within the technologically advanced nations. On the whole, the selection criteria secured cases where advancements in the IoT and big data technologies and their novel applications for sustainability, coupled with future visions in this regard, are present.

Environmentally data-driven smart sustainable cities: Stockholm and Barcelona

The cases of Stockholm and Barcelona have been selected using a theoretical sampling approach (Yin 1984, 2009). The Cities of Stockholm and Barcelona fall within the category of large cities in Europe. The area of Stockholm has an approximate size of 188 km and a population of 1,632,798 million habitants, and the area of Barcelona has an approximate size of 101.9 km^2 and a population of 5.586 million habitants. Additionally, the success of the two cities in the field of sustainable urbanism and smart urbanism, respectively, makes their strategies and solutions an ideal sample to analyze. This assertion can be easily demonstrated considering the multiple awards the two cities have received during recent years and their international positioning. This pertains to Stockholm as both a sustainable city and a smart sustainable city (e.g., Akande et al. 2018; Bibri 2020a, b; European Green Capital 2009; Holmstedt et al. 2017; Kramers et al. 2016; Stockholm City 2009, Stockholm City 2010, Stockholm City 2018, Stockholm City 2020). Stockholm is at the forefront of ecological/environmental thinking. It has very strong environmental policies and is focused on improving the quality of life of its citizens (Lindström and Eriksson 1993; Stockholm City 2018) with support of advanced technologies (Bibri 2020a; Wouter et al. 2018). According to the City of Stockholm, an IoT–based infrastructure is highly important for, and the backbone for building, smart sustainable cities nowadays (Bibri and Krogstie 2020a). As stated by Johansson (2018), a project leader, the reason for establishing the IoT infrastructure in the city "is because we have a lot of challenges. We know that using the smart technologies can help us to be a better city, for the people that live there, work there and even the people that are visiting us." He also stated that the environmental department in the city is active with smart technologies. During the period 2015–2016, an ICT network was established in the City of Stockholm to find a more comprehensive way of using ICT, and the digital development department of the city was established with a much broader take on ICT (Kramers et al. 2016). The city has recently taken concrete actions for using data-driven technologies to reach its environmental targets by 2040, in particular in relation to the initiative of SRS (Bibri and Krogstie 2020a). This smart eco–city district starts with a common vision in smart planning on the basis of the IoT technology (The Nordics 2017).

The international positioning pertains to Barcelona as a smart city (e.g., Achaerandio et al. 2011; Ajuntament de Barcelona 2014a; Cohen 2012a, b, 2014; European Commission 2014; Eden Strategy Institute 2018; Manville et al. 2014; Nikitin et al. 2016) and a sustainable smart city (e.g., Bibri and Krogstie 2020b; Noori et al. 2020). Indeed, Barcelona is taking concrete actions for implementing the applied data-driven technology solutions developed for urban operational functioning and planning as part of the city management to improve and advance sustainability—thereby evolving into what has been termed as a data-driven sustainable smart city (Bibri 2020a). Barcelona is strongly committed to becoming a smart city and a show-case for the rest of the world in sustainable urban development (Mora and Bolici 2016). This is clearly figured in the public statements proposed by different local government representatives (see, e.g., Ajuntament de Barcelona 2011, 2012, 2013, 2014b, 2014c). One of the strategies of the Municipal Action Program is called *"urban renewal"* and is associated with a precise strategic commitment to transform *"Barcelona into a sustainable, smart urban model at the service of its residents" (*Mora and Bolici 2016, p. 3).

In light of the above, the two cities demonstrate exemplary practical initiatives as regards the integration of data-driven solutions and sustainable development strategies. As such, they may be seen as successful examples of the environmentally data-driven smart sustainable city, as well as critical cases in environmental sustainability. This is further due to the national focus on environmental sustainability in Stockholm and the national focus on ICT in Barcelona, with visible shared goals and visions in regard to these foci. All in all, the selection secured cases where advances in the IoT and big data technologies and their novel applications for environmental sustainability, coupled with future visions and goals, are present.

Subject, object, unit of analysis, and data collection method

Whatever the frame of reference for the choice of the subject of the case study, there is a distinction to be made between the subject and the object of the case study. The subject is the "practical, historical unity" through which the theoretical focus of the study is being viewed (Wieviorka 1992), and the object is the analytical frame within which the study is conducted and which the case illuminates (Thomas 2011). Compact urbanism, ecological urbanism, data-driven smart urbanism, and environmentally data-driven smart sustainable urbanism were identified as the universe—that is, the class of events—of which a group of two cases in each of the four case studies represent instances. The subjects of the four case studies, which are the six cases themselves, are thus the instances of these four urban phenomena, and the latter—the phenomena—comprise the analytical frame. This is based on the typology proposed by Thomas (2011) for the case study following a definition wherein various layers of classificatory principle are disaggregated (Fig. 2).

For a "case" to exist, we must be able to identify a characteristic unit … This unit must be observed, but it has no meaning in itself. It is significant only if an observer … can refer it to an analytical category or theory. It does not suffice to observe a social phenomenon, historical event, or set of behaviors in order to declare them to be "cases." If you want to talk about a "case," you also need the means of interpreting it or placing it in a context (Wieviorka 1992, p. 160).

The aim of the futures study constitutes the basis for determining the unit of analysis concerning the four case studies. The objects of the four case studies have key differences as well as some overlaps, so do the units of the analyses. The new model of urbanism that the futures study is concerned with represents the amalgamation of the leading paradigms of urbanism. As to the first case study, the unit of analysis, the entity that frames what can be analyzed, is the design strategies of the compact city and the extent to which they support and balance the environmental, economic, and social goals of sustainability. Concerning the second case study, the unit of analysis is the strategies and solutions of the eco-city and the extent to which they integrate the environmental, economic, and social goals of sustainability. As regards the third case study, the unit of analysis is the applied solutions of the emerging data-driven smart city for sustainability. With respect to the fourth case study, the unit of analysis is the data-driven solutions applied in the sustainable city and the smart city for environmental sustainability.

The unit of analysis is essential to focalizing, framing, and managing the data collection and analysis. The qualitative data were extracted from multiple sources of evidence identified with a series of searches performed in various online databases. The relevant archive records and documents produced by public and private organizations were considered as primary sources (i.e., master plans, comprehensive plans, visions, strategies, agendas, project descriptions, presentations, etc.). In addition, a wealth of data was acquired from other documents produced by organizations or researchers not directly involved in the four initiatives of the city cases. These sources were considered as secondary (i.e., reports, newspaper articles, journal and online articles, conference proceedings, research project deliverables, etc.).

Another supporting form of the primary data used in regard to the first case study was face–to–face and telephone interviews conducted with a total of 10 interviewees, including planners, architects, developers, consultants, and administrative servants, These interviewees were mostly involved in those areas associated with the challenging and conflicting issues of the compact city initiatives. These issues were identified based on the previous empirical studies carried out in relevance to the compact city model, as well as on the arguments advanced by the critics of this model in the literature. One of the key objectives of the interviews was to corroborate any progress made by the two cases investigated as to the development and implementation of new measures to address the common environmental and social issues of the compact city.

As regards the second case study, the other supported form of the primary data was face-to-face and telephone interviews with a total of 10 interviewees, including planners, architects, developers, project leaders, and administrative servants. They were selected from the ongoing projects of SRS and Western Harbor, especially those working within the areas that involve contentious and challenging issues based on both the outcome of the previous empirical studies carried out in relevance to the eco-city model, as well as the arguments advanced by the critics of this model in the literature. One of the key objectives of the interviews was to corroborate the progress made by the

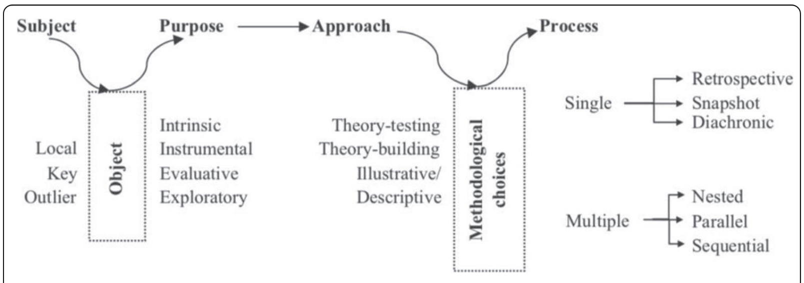

Fig. 2 A typology of case study. Source: Thomas (2011)

Municipalities of Stockholm and Malmö as to the development and implementation of new measures to address the issues related to the economic and social dimensions of sustainability. As regards the environmental dimension of sustainability, the objective of the interviews was to document the practical advances claimed to be made in the field of sustainable urban development, as well as the extent to which the eco-city district strategies have been implemented according to the plan.

The interviews were mostly unstructured. They were intended to be used in ways that can be adapted to the interviewees' roles and interests. This means that the interviewees were asked different questions. The findings were reported in a form of complementing, substantiating, and conflicting statements. Additionally, a set of face–to–face and telephone conversations were conducted with some researchers and scholars at Lund University and Gothenburg University in relation to the first case study, and Stockholm and Malmö in relation to the second case study. Within the framework of the compact city, they were particularly important in providing further insights into some ongoing projects for strengthening the influence of the environmental and social goals of sustainability over urban planning and development practices in the ambit of sustainable cities. In terms of the eco-city, they provided insights into some ongoing projects and useful knowledge regarding the core dimension of environmental sustainability and the efforts being made to support the balancing of the three goals of sustainability through new endeavors focusing on social and economic issues in response to the agenda of sustainable development. As far as the face-to-face conversations are concerned, they took place with no schedule set in advance, whenever the circumstances allowed.

Analytical method: thematic analysis

To identify, analyze, interpret, and report the case–based themes, a thematic analysis approach was designed and employed. This qualitative analytical approach was deemed suitable given the form of knowledge and insights that we sought to gain from the qualitative data gathered in connection with the cases studies. Generally, it is up to the researcher to decide if this analytical approach is suitable for their research design, and whether it can be adapted for their own uses or purposes.

Thematic analysis is particularly, albeit not exclusively, associated with the analysis of textual material. It emphasizes identifying, analyzing, interpreting, and reporting themes, i.e., important patterns of meaning within the qualitative data that can be used to address the research problem. Braun and Clarke (2006) suggest that thematic analysis is flexible in terms of research design given that it is not dependent on any particular theory: multiple theories can be applied to this process across a variety of epistemologies. Also, thematic analysis is more appropriate when dealing with a large body of qualitative data. In addition to providing a flexible way of data analysis, thematic analysis permits researchers with different methodological backgrounds to engage in such type of analysis (Braun and Clarke 2006). However, this flexibility can lead to inconsistency and a lack of coherence when developing themes derived from the research data (Holloway and Todres 2003). Moreover, thematic analysis minimally organizes and describes qualitative data in detail, involves the risk of missing nuances in the data when used in a theoretical vacuum, does not allow researchers to make technical claims about language usage (Braun and Clarke 2006), and relies on the researchers' judgement. The latter relates to the issue of reliability due to the numerous potential ways of data interpretations and the potential for researcher subjectivity to distort the analysis. There is no one accurate interpretation of data, interpretations reflect the positioning of the researchers. Therefore, it is important for them to reflect carefully on their own interpretations and continually on how they are shaping the evolving analysis by paying close attention to the data to achieve a quality analysis. Thematic analysis takes as its analytic object meaning by attending to the content of text in its various forms, while keeping in mind how the data are generated, attending to some form of context for interpretation purposes. This pertains particularly to secondary data. Secondary analysis usually involves some degree of distance from the original data as regards to the research questions and place where the data were gathered (see Elliott et al. 2013 for a discussion).

Thematic analysis has proliferated so that it can be diverse. Hence, it is best thought of as an umbrella term for a variety of different approaches, which are underpinned by different philosophical assumptions as well as divergent in regard to procedures. Braun and Clarke (2006) distinguish between three main types of thematic analysis: coding reliability approaches, code book approaches, and reflexive approaches. Another classification entails inductive and deductive types of thematic analysis. The inductive approach involves allowing the data to determine the set of themes to be identified, and the deductive approach involves handling the data with some preconceived themes that are expected to be reflected in the data based on existing knowledge (descriptive theory). The latter is applied in the case studies carried out on compact cities and eco-cities. With respect to the former, it is applied in the case studies performed on data-driven smart cities and environmentally data-driven smart sustainable cities. This is justified by the fact that these two approaches to urbanism are an emerging area of research and practice. That is to say, there is no established theoretical framework that gives a strong idea of what kind of themes to expect to find in the data (deductive). Indeed, the intent is to develop a framework based on what can be discovered as themes (inductive). Accordingly, these themes are not predetermined following the inductive approach. As an inductive analytical approach, thematic analysis can be used to address the different types of questions posed by researchers to produce complex conceptual cross–examinations of meaning in the qualitative data. In addition, this approach to thematic analysis is appropriate when analyzing and synthesizing a large body of data—in the form of empirical studies, exploratory studies, conceptual frameworks, descriptive accounts, reviews, and so on. It has also been applied to produce theory–driven analyses. All in all, the researchers use thematic analysis as a means to gain insights and knowledge from the qualitative data gathered.

The main four steps of the analytical approach applied in the four case studies, with some slight differences, are as follows:

1. Reviewing the multiple sources of the data related to the selected cases. The outcomes of this process are numerous themes that are associated with the four models of urbanism in question. It is important to have a comprehensive understanding of the content of the planning documents and multidisciplinary literature, as well as to be familiarized with all aspects of the data collected. This step provides the foundation for the subsequent analysis.

2. Pattern recognition (searching for themes) entails the ability to see patterns in seemingly random information. The aim is to note major patterns within the result of the first step. The second step looks for similarities within the sample and codes the results by concepts. Coding involves identifying passages of text that are linked by a common theme allowing to index the text into categories and therefore establish a framework of thematic ideas about it. In this step, the preliminary codes identified are the features of data that appear meaningful and interesting, and the relevant data extracts are sorted according to the overarching themes. Accordingly, coding facilitates the management of the vast amount of data that has been collected. It is important to allude to the relationship between codes and themes.
3. Revising themes is about combining, separating, refining, or discarding initial themes. This relates mainly to the inductive approach to thematic analysis. Data within the themes should cohere together meaningfully and be clear and identifiable as regards the distinction between these themes. A thematic 'map' is generated from this step.
4. Producing the report involves transforming the analysis into an interpretable piece of writing by using vivid and compelling data extracts that relate to the overarching themes, research questions, and literature. This is a fundamental step for supporting future comparative research and cross-case analysis (Yin 1984; Patton 2012). The report must go beyond a mere description of the preconceived themes and portray an analysis supported with the empirical evidence that addresses the research questions.

This analytical strategy has allowed to analyze the selected cases considering the different perspectives of multiple observers. Moreover, the final description of the process has gained greater strength thanks to the triangulation made possible by the use of multiple sources of evidence (George and Bennett 2005; Yin 1984; Voss et al. 2002).

As to the results from the thematic analysis of the four case studies, the interested reader can be directed to Bibri and Krogstie (2020d). The integrated framework illustrated in Fig. 3 was derived based on the thematic analysis in terms of the core dimensions of compact cities, eco-cities, data-driven smart cities, and environmentally data-driven smart sustainable cities. It attempts to capture in a structured manner the underlying components of the novel model for data-driven smart sustainable cities of the future. In this respect, there are four basic categories of criteria that are used in defining the data-driven smart sustainable city of the future, namely compact urban strategies, ecological urban strategies, data-driven technologies and solutions for sustainability, and data-oriented competences. The basic idea revolves around the integration of the strategies of sustainable cities with the applied solutions of data-driven smart cities. This is predicated on the assumption that big data technologies and their novel applications associated with the informational landscape of smart cities have great potential to improve and advance the design strategies and technology solutions pertaining to the physical landscape of sustainable cities in terms of their contribution to the environmental, economic, and social goals of sustainability.

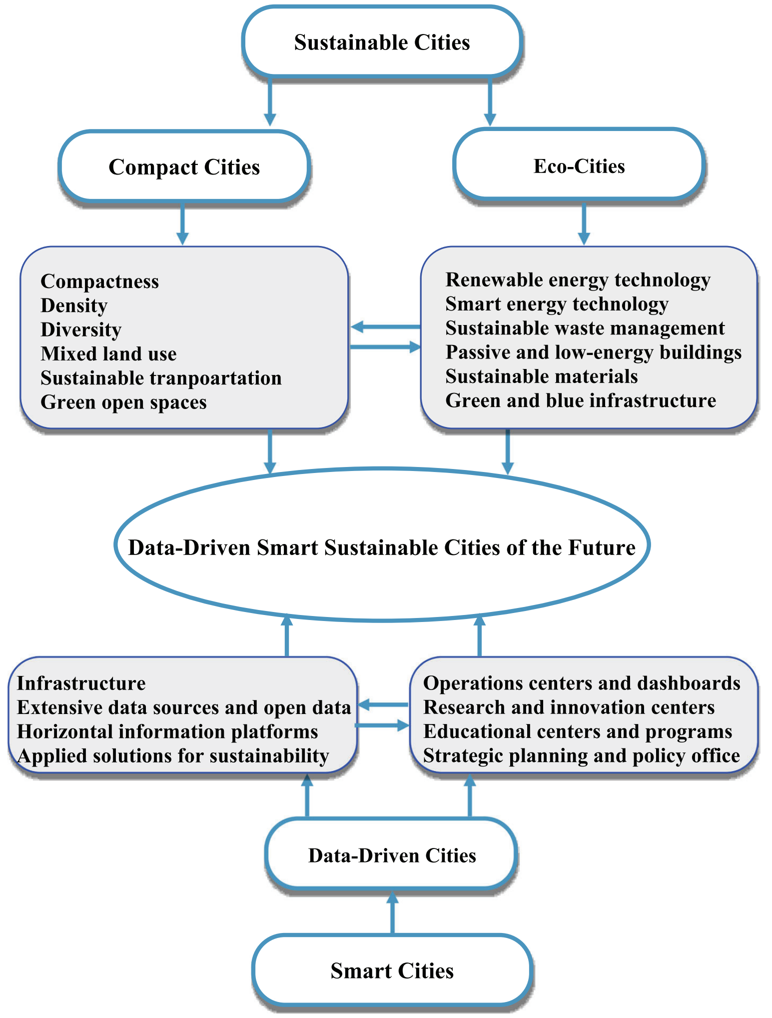

Fig. 3 A framework for strategic sustainable urban development planning

Conclusion

Backcasting belongs to the normative category of futures studies. A number of futures studies using the normative backcasting approach have highlighted its efficacy in indicating pathways for sustainability transitions in terms of the ability to produce a desired result, thereby its role and relevance in supporting policymakers and facilitating and guiding their actions with respect to strategic sustainable development. The purpose of the backcasting-oriented futures study is to create knowledge that can be used to guide complex urban transitions towards urban sustainability in an increasingly technologized and urbanized world. In this sense, backcasting can be viewed as changing mindsets about how sustainable cities function by being designed in ways that allow to monitor, understand, analyze and plan their systems to improve sustainability, efficiency, resilience, equity, and the quality of life. In the data-driven smart sustainable city of the future as a complex system, backcasting is an effective approach to align various measures with each other and to ensure that each activity is the logical platform for the next one.

This paper described, discussed, and justified the methodological framework applied in the futures study concerned with data-driven smart sustainable urbanism as a form of transformative change towards sustainability. The novelty of this work lies in the integration of a set of principles underlying several normative backcasting approaches with descriptive case study design to devise a framework for strategic urban planning whose core objective is clarifying which city model is desired and working towards that goal.

Visionary images of a long-term future based on normative backcasting can spur innovative thinking about and accelerate the movement towards achieving the goals of sustainability. The data-driven smart sustainable city of the future as a new paradigm of urbanism can be seen as the most important arena for sustainability transitions in the era of big data. It offers a clear prospect to instigate a major transformative change by synergistically linking the agendas of urban development , sustainable development, and technological development to add a whole new dimension to sustainability in terms of its advancement. This kind of drastic change requires a multifaceted process of strategic planning with an innovative vision that takes the sustainable city from its present state to a desirable future state**.** Backcasting as the most suitable approach to strategic sustainability planning can play a pivotal role in this regard by determining decisive steps and guiding decision–making processes to achieve the long-term desired outcomes. Moreover, it allows for a better understanding of future opportunities and exploring the implications of alternative development paths that can be relied on to mitigate or avoid the potentially negative impacts of the future. It is a commonly held view that strategic planning based on normative backcasting scenarios can change development paths. When applied in sustainability planning, backcasting can also increase the likelihood to envision certain changes. The interest in the pursuit of the data-driven smart sustainable city of the future is motivated by the aspiration to influence, inspire, as well as transform the future of the sustainable city by changing the path of its development or redirecting its transition to a better future in the light of the emerging paradigm of big data science and analytics. Therefore, it is scholarly worthy to venture some thoughts about where it might be useful to channel the efforts now and in the future in the sphere of what has been termed "data-driven smart sustainable urbanism."

The outcomes of the four case studies carried out are intended to guide and inform the futures study in terms of the underlying components of the novel model for data-driven smart sustainable cities of the future. By carefully studying any unit of a certain universe, we are in terms of knowing some general aspects of it, at least a perspective that guides ongoing or subsequent research (Wieviorka 1992). Case studies often represent the first scholarly toe in the water in the new areas of research. In this context, the six cases were investigated to identify the design strategies of sustainable cities and the data-driven solutions of smart cities that are needed to develop the data-driven smart sustainable city of the future as a new paradigm of urbanism.

The application of and sound debate about the value, validity, and capability of case study research have strengthened the efficacy of the case study approach as a powerful form of qualitative research. Moreover, case studies are useful for formulating concepts, which are an important aspect of theory construction (Mahoney 2010). The concepts used in qualitative research tend to have higher conceptual validity than concepts used in quantitative research due to conceptual stretching: the unintentional comparison of dissimilar cases (George and Bennett 2005)· Case studies add descriptive richness (Collier 2011). However, a commonly described limit of case studies is that they do not lend themselves to generalizability. Additionally, George and Bennett (2005) note that a common problem in case study research is that of reconciling conflicting interpretations of the same.

The case study and backcasting approaches are both regarded as a tool with which theories can be supported and their effects can be demonstrated, as well as facts can be developed. The purpose of analyzing and evaluating the six cases associated with the futures study is to provide the theoretical and practical foundations necessary for backcasting the future phenomenon of the data-driven smart sustainable city. In this respect, it is important first and foremost to define which characteristics of the future state of this phenomenon are meaningful, beneficial, and interesting, and should therefore be incorporated in the backcasting (see Bibri and Krogstie 2020d for further details). This involves both the theoretical underpinnings and the emerging practices that are of pertinence and importance as a basis for the backcasting. With respect to the former, the material needed to make the backcasting depends on how strong the theoretical frameworks we have about the envisioned phenomenon of the data-driven smart sustainable city and its internal relationships from a conceptual, disciplinary, and discursive perspective (see Bibri 2018a, d, 2019a, c, d, 2020a; Bibri and Krogstie 2016, 2017b for further details). Commonly, quite a strong basis for backcasting any future phenomenon is available when there are frameworks that can explain, support, and justify that phenomenon. On the whole, this scholarly backcasting endeavor combines the theoretical analysis and the empirical investigation to develop the data-driven smart sustainable city of the future.

Abbreviations
CTA: Constructive Technology Assessment; FSSD: Framework for Strategic Sustainable Development; ICT: Information and Communication Technology; IoT: Internet of Things; SDG: Sustainable Development Goal; STD: Sustainable Technology Development; SRS: Stockholm Royal Seaport; SASD: Strategic Approach to Sustainable Development; SUMP: Sustainable Urban Mobility Planning; TNS: The Natural Step

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Paper 6

Compact City Planning and Development: Emerging Practices and Strategies for Achieving the Goals of Sustainability

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Compact city planning and development: Emerging practices and strategies for achieving the goals of sustainability

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ABSTRACT

The compact city is one of the leading paradigms of sustainable urbanism. Compact city planning and development has, over the last 30 years or so, been the preferred response to the challenges of sustainable development. It is strongly promoted by global and local policies due to its positive outcomes in terms of contributing to the economic, environmental, and social goals of sustainability. This paper examines how the compact city model is practiced and justified in urban planning and development with respect to the three dimensions of sustainability, and whether any progress has been made in this regard. To illuminate this urban phenomenon accordingly, a descriptive case study is adopted as a qualitative research methodology where the empirical basis is mainly formed by the official plans and documents of two Swedish cities: Gothenburg and Helsingborg, in combination with qualitative interview data and secondary data. This study shows that compactness, density, diversity, mixed land use, sustainable transportation, and green space are the core design strategies of compact city planning and development, with the latter being contextually linked to the concept of green structure, an institutional setup under which the two cities operate. Moreover, at the core of the compact city model is the clear synergy between the underlying strategies in terms of their cooperation to produce combined effects greater than the sum of their separate effects with respect to the benefits of sustainability as to its tripartite composition. Further, this study demonstrates that the compact city model as practiced by the two cities is justified by its ability to contribute to the economic, environmental, and social goals of sustainability. However, the economic goals dominate over the environmental and social goals, notwithstanding the claim about the three dimensions of sustainability being equally important at the discursive level. Nevertheless, new measures are being developed and implemented to strengthen their influence over urban planning and development practices towards balancing the three goals of sustainability.

1. Introduction

Compact cities have, since the early 1990s, been one of the leading global paradigms of sustainable urbanism. In the European Union Green Paper of the Urban Environment, the compact city model was advocated as the most sustainable approach to urbanism (CEC, 1990). A number of recent UN–Habitat reports and policy papers argue that the compact city model has positive effects on resource efficiency, economy, citizen health, social cohesion, and cultural dynamics (UN–Habitat 2011, 2014a, 2014c, 2015). Indeed, according to many studies (e.g., Arbury, 2005; Burton, 2002; Bibri, 2020a, b; Bibri and Krogstie, 2017b; Hofstad, 2012; Jabareen, 2006; Næss et al., 2011; Newman and Kenworthy, 1999; Williams et al., 2000), the compact city can promote sustainability by reducing the amount of travel and shortening commute time; decreasing car dependency; lowering per capita rates of energy use; limiting the consumption of building and infrastructure materials; mitigating pollution; maintaining the diversity for choice among workplaces, service facilities, and social contacts; and limiting the loss of green and natural areas. This is justified by the fact that the compact city emphasizes the intensification of development and activities, creates limits to urban growth, encourage land use and social mixes, and focuses on the importance of public transportation and the quality of urban design. All

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in all, the compact city harnesses the advantages of agglomeration and taps into the tremendous variety of environmental, economic, and social benefits it has to offer through proper planning and development.

The benefits of the compact city, as research from around the globe suggests, are far from certain or not guaranteed as desired outcomes. This relates to the issues argued against by the critics of the compact city model that should be addressed so that it can gain in more popularity. By and large, most of these issues pertain to the unforeseen consequences and unanticipated effects of the compact urban form that fall under what is called in urban planning"wicked problems" a term that has gained more currency in urban policy analysis after the adoption of sustainable development within urban planning since the early 1990s. These issues are often overlooked as a result of failing to approach this urban system from a holistic perspective, or of treating it in too immediate and simplistic term. Rittel and Webber (1973), the first to define the term, associate wicked problems with urban planning, arguing that the essential character of wicked problems is that they cannot be solved in practice by a central planner. Wicked problems are so complex and dependent on so many factors that it is hard to grasp what exactly the problem is or how to tackle it.

In addition, in the current climate of the unprecedented urbanization and increased uncertainty of the world, it may be more challenging for cities in developed countries to configure themselves more sustainably. The predicted 70% rate of urbanization by 2050 (United Nations, 2015) reveals that the sustainability of the urban environment will be a key factor in the global resilience to the forthcoming changes. This implies that the city governments in these countries will face significant challenges related to environmental, economic, and social sustainability due to the issues engendered by urban growth. These include increased energy consumption, pollution, toxic waste disposal, resource depletion, inefficient management of urban infrastructures and facilities, ineffective planning processes and decision–making systems, poor housing and working conditions, saturated transport networks, endemic congestion, social inequality, and socio-economic disparity (Bibri, 2019a; Bibri and Krogstie, 2017a), In a nutshell, urban growth raises a variety of problems that tend to jeopardize the sustainability of cities as it puts an enormous strain on urban systems and great demand on natural resources. Furthermore, cities in developed countries are likely to experience an even more rapid decline in average densities through more sprawling patterns, reducing the ability of city–regions to support themselves, unless they adopt and pursue more compact development strategies.

A large body of work has addressed the claimed effects of the compact city model achieved through planning practices and development strategies. More specifically, the discussion has focused on the extent to which this model produces the claimed environmental, economic, and social benefits of sustainability (e.g., Bibri, 2020b; Burton, 2002; Jenks and Jones, 2010; Hofstad, 2012; Lin and Yang, 2006). Here the focus is often on the design strategies of the compact city model (e.g., Bibri 2018a; Bibri and Krogstie, 2017b; Boussauw et al., 2012; Dumreicher et al., 2000; Jabareen, 2006; Kärrholm, 2011; Van Bueren et al., 2011; Williams et al., 2000). This line of research directs attention to their link to the goals of sustainability as to its tripartite composition. As such, it opens the way for cross–domain analyses with regard to integrating environmental, economic, and social aspects (e.g., Krueger and Gibbs, 2007). This paper follows this path by examining how the compact city model is practiced and justified in urban planning and development with respect to the three dimensions of sustainability, and whether any progress has been made in this regard. Accordingly, the main research questions driving this paper are:

1 What are the prevalent design strategies of the compact city model, and in what ways do they mutually complement, or beneficially affect, one another in terms of producing the expected benefits of sustainability?
2 To what extent does the compact city model contribute to and balance the three goals of sustainability?

To illuminate the phenomenon of the compact city accordingly, a descriptive case study is adopted as a qualitative research methodology where the empirical basis is mainly formed by the official plans and documents of the Cities of Gothenburg and Helsingborg, Sweden, in combination with qualitative interview data and secondary data. We chose these cities for several reasons. First, they are among the largest cities in Sweden's fastest growing urban landscapes. Second, they are among the Sweden's most ambitious cities as regards sustainable planning, producing a great deal of planning material and ideas about sustainable urban form.

This paper demonstrates how the compact city model is practiced and justified by the two Swedish cities in their urban planning and development. Forming the basis for the planning and development of the future of these cities, their visions, policies, and strategies are developed along the lines of the argument supported by European Union policy documents that a compact city structure has positive effects on efficient use of resources, economic development, and citizen well–being (CEC 2011); that compact city policies result in reduced energy consumption and emissions in transportation at different spatial scales, in conservation of farmlands and biodiversity, and in reduction of infrastructure cost and increase of labour productivity (OECD, 2012a); and that cultural, social, and political dynamics are promoted by density, proximity, and diverse choices available within compact cities (CEC, 1990).

This paper unfolds as follows. Section 2 provides a relevant topical literature review of the compact city. Section 3 outlines, justifies, and elaborates the research methodology adopted in this study. Section 4 presents the results. Section 5 discusses the results and how they are interpreted in perspective of previous studies. Finally, the paper concludes, in Section 6, by drawing the main findings, providing some reflections, and suggesting avenues for future research.

2. Literature review

2.1. The compact city as an approach to sustainable cities

Rooted in the study of the relationship of urban planning and sustainable development in a rapidly urbanizing world, sustainable urbanism is concerned with the study of cities and the practices and strategies to design and develop them that focus on promoting their long-term resilience and viability through reducing material use, lowering energy consumption, mitigating pollution, and minimizing waste, as well as improving social equity and well-being. The compact city is the central paradigm of sustainable urbanism.

There are multiple views on what a sustainable city should be or look like and thus various ways of conceptualizing it. Generally, a sustainable city can be understood as a set of approaches to practically applying the knowledge about sustainability to the planning and design of existing and new cities. It represents an instance of sustainable urban development, a strategic approach to achieving the long–term goals of urban sustainability. Accordingly, it needs to balance between the environmental, economic, and social goals of sustainability as an integrated process. Such balance has more opportunity to make the city greener, fairer, and more profitable for all stakeholders of the city.

Sustainable cities have been the leading paradigm of urbanism for more than three decades. However, there are different approaches to sustainable cities, which are identified as models of sustainable urban forms, including compact cities, eco–cities, green cities, new urbanism, landscape urbanism, and urban containment. Of these models, compact cities are ofte advocated as more sustainable.

While there is no definite definition of the compact city in the literature, most of the available definitions tend to share the core dimensions of this model of sustainable urban form. To Burton (2002), the so-called compact city is taken to mean "a relatively high–density, mixed–use city, based on an efficient public transport system and dimensions that encourage walking and cycling." According to other views (e.g., Jenks, Burton and Williams, 1996a; b; Williams et al., 2000), the compact city is characterized by high–density and mixed land use with no sprawl. Dantzig and Saaty (1973) provide an explanation of the densification characteristics based on three elements: the urban form, the space, and the social functions (Table 1).

2.2. Compact city dimensions, issues, policies, and perspectives

While many studies have been carried out on the compact city based on a variety of approaches, they share the core dimensions of this model of sustainable urban form, with a slight difference in details as illustrated in Table 2. This serves to inform and guide the selection of the design strategies to be studied with respect to the cases of Gothenburg and Helsingborg. In this context, the term 'principle' means a proposition that serves as the foundation for the compact city model, and the term 'strategy' denotes an approach that is used to achieve the goals of sustainability.

There is a large body of empirical work on compact cities, especially in the form of case studies. A key strand of this research focuses on a range of environmental, economic, and/or social aspects and the associated policies and planning practices. A set of recent case studies is selected and compiled in Table 3. Generally, studies on compact cities are approached from a variety of perspectives, including urban theory, planning theory, planning practice, design practice, policy, resilience, sustainability, morphology, complexity theory, systems thinking, action net theory, actor network theory, spatial analysis, regenerative design, economics, in addition to comparative and discursive studies. This study approaches the topic of the compact city from the perspective of planning and design practices and strategies through which this model can be realized to support and balance between the three goals of sustainability.

Furthermore, many cities having the highest level of sustainable development practices have been studied on their compact development with the aim to contextualize the outcome to become practically applicable in other cities. Accordingly, lessons can (and should) be learned from other cities around the world. It is well understood that there cannot be a set of rigid strategic guidelines that should be strictly followed and implemented anywhere around the world to achieve sustainable urban forms. Sustainability depends on several intertwined factors that should fit the local context. In view of that, each city should tap into its local opportunities and capabilities as well as assesses its constraints and potentials from a more integrated perspective given the complexity associated with the social, economic, and environmental aspects of the city (Bibri, 2020a, b; Newman and Jennings, 2008). In some instances, cities are evidently incomparable both in scale and in socio–cultural, political, and historical contexts, but the comparison can still be undertaken regarding the relative proportions of density and diversity across urban areas. Yet, even if several attempts have been undertaken to establish 'compact city' indexes, the heterogeneity of the concepts of density (Churchman, 1999; Berghauser Pont and Haupt, 2010; Manaugh and Kreider, 2013), diversity (Manaugh and Kreider, 2013), and urban form (Hillier, 1996; Marshall, 2005), coupled with the prevalence of different indexes (Lee et al., 2015), remains problematic for policy implementation. Therefore, the classifications listed in the UN–Habitat's and other policy documents lack concrete guidelines for global implementation (Lim and Kain, 2016). All in all, each city should deal with its own urban specificities in regard to development agenda and form aspects, applying compact city discourse and implementing policies to improve the health of the city and the quality of life for the citizens.

Due to the above inconsistencies in urban research and their effect on practice as to planning policy, the concept "compact city" risks becoming a "boundary object" (Star and Griesemer, 1989) similar to the concept "sustainable development "(Muraca and Voget–Kleschin, 2011). As a means of translation used to connect different, or create intersections of separate, social worlds, a boundary object is interpreted and used differently by various actors or across communities in light of their own experiences, needs, constraints, and/or biases. In this case, the concept of the compact city becomes vague enough to justify any type of urban development (Leffers, 2015).

Table 1
Densification characteristics.

Urban form features	Spatial features	Social functions
• High dense settlements	• Mixed land use	• Social fairness
• Less dependence on automobile	• Diversity of life	• Self-sufficiency of daily life
• Clear boundary from surrounding areas	• Clear identity	• Independence of government

Table 2
Core dimensions of the compact urban form.

Scholars and Organizations	Focus of Studies	Dimensions
(UN–Habitat 2015)	Strategy of sustainable neighborhood planning	1. Adequate space for streets 2. Efficient street network 3. High density 4. Mixed land uses 5. Social mix 6. Limited land use specialization
Jabareen (2006)	Design concepts of sustainable urban forms and their contribution to sustainability	1. Compactness 2. Density 3. Mixed land uses 4. Diversity 5. Sustainable transport
Kotharkar et al. (2014)	Measuring compact urban form	1. Density 2. Density Distribution 3. Mixed land uses 4. Transportation network 5. Accessibility 6. Shape
Jones and Macdonald (2004)	Sustainable urban form components and economic sustainability	1. Mixture of Land uses 2. Density 3. Transport infrastructure 4. Characteristics of built environment 5. Layout
(Dempsey et al., 2010)	Sustainable urban form components	1. Density 2. Mixed land uses 3. Transport infrastructure 4. Accessibility 5. Built environment characteristics 6. Urban layout
Song and Knaap (2004)	Quantitative measure of urban form	1. Density 2. Mixed land uses 3. Pedestrian access 4. Accessibility 5. Street design and circulation system
OECD (2012b)	Policies of compact city: a comparative assessment	1. Compactness 2. Impact of compact city policies
Bertaud (2001)	Analysis of spatial organization of large cities	1. Spatial Distribution of Population 2. Spatial Distribution of Trips 3. Average density and land use 4. Density profile 5. Population by distance to gravity center

Table 3
Examples of case studies on compact cities.

Country	Issues	Policies
Paris, France (OECD, 2012b)	Urban development Car dependency Loss of green space	Regional development agenda Grand Paris Express connection
Hong Kong, China (Lau et al., 2002)	Urban development Traffic congestion Urban sprawl growth High immigration Flat land shortage	The Concept of Vertical City The Concept of Compact City The Concept of Sky City
Melbourne, Australia (OECD, 2012b)	Decline in economic sectors Rapid urban growth Increased car and truck ownership Urban sprawl growth	Revitalization of Central Melbourne Deregulation policies on and conversion of land use
Amsterdam, Netherland (Nabielek, 2012)	Scattered development Increased congestion High urbanization Urban sprawl growth High immigration	The Structure Plan The National Environmental Policy Plan The National Policy on Spatial Planning
Tokyo and Gothenburg (Lim and Kain, 2016)	Density of built objects Scales of built objects Distribution of the diversity of built objects	The Concept of Compact City Comprehensive Plan for Gothenburg Master Plan for Tokyo Planning by Design Planning by Developmental Control Planning by Coding/ Rule–based Planning
Auckland, New Zealand (Arbury, 2005)	Rapid urban growth Car dependency Transportation system Urban sprawl growth	Regional Growth Strategy for Compact Development Regional Growth Strategy 2050
Toyama, Japan (OECD, 2012b; Suzuki et al., 2010)	Increasing car dependency Population density decline Urban centers decline Agricultural land decline	Master Plan for Toyama City Toyama Compact City Model The City's Density Target and Grant Program

2.3. The Compact city ideal

As widely acknowledged in sustainable urban planning and development, the image of the compact city has proven to be a highly influential translation of what a sustainable city should be, carried by the significance and relevance of the design strategies of this model of sustainable urban form. As a desirable form, the compact city indeed secures a development that is environmentally sound, economically viable, and socially beneficial (Bibri and Krogstie, 2020c; Burton, 2002; Dempsey, 2010; Jenks and Dempsey, 2005; Jenks and Jones, 2010), especially when it is strategically planned and well–designed prior to its development. As such, it can be viewed as an all–encompassing understanding of urban complexities and an all-embracing conception of planning practices and development strategies. Table 4 presents the main sustainability benefits of the compact city, drawing on many theorists and scholars (e.g., Bibri, 2020a, b; Bibri and Krogstie, 2017b; Burton, 2000, 2001; CEC, 1990; Dempsey and Jenks, 2010; Frey, 1999; Hofstad, 2012; Jabareen, 2006; Jenks and Jones et al., 2010a; Jones et al., 2010; Alberti, 2000; Van and Senior, 2000; Newman and Kenworthy, 1999; Williams et al., 2000).

Table 4
The main sustainability benefits of the compact city.

Environmental sustainability
- Lowering per capita rates of energy use and requiring less and cheaper per capita infrastructure provision
- Lowering energy consumption and reducing pollution due to the proximity to workplaces, services, facilities, and public spaces
- Decreasing travel needs and costs and shortening commute times
- Minimizing the transportation of energy, materials, water, and products due to the compactness of the built environment
- Optimizing the efficiency of the public transport system
- Limiting the consumption of building and infrastructure materials
- Reducing car dependency and thus CO_2 emissions through encouraging walking and cycling
- Conserving energy by combining heat and power provisions made possible by population densities
- Reducing the pressure on ecosystem services and biodiversity provided by green and natural areas.
- Limiting the loss of green and natural areas
- Protecting rural and agricultural land from further development

Economic sustainability
- Supporting local services and businesses through population densities, i.e., providing a larger customer basis for commercial activities
- Revitalizing city centers through the promotion of densely built dwellings, shops, businesses, and accessible infrastructure and facilities
- Extending and enhancing public transportation infrastructure and facilities
- Creating proximity between employees and their workplaces
- Promoting greater diversity among employers and thus greater diversity of job possibilities
- Increasing the likelihood of workers finding jobs that match their skills, which results in higher productivity
- Maintaining the diversity for choice among workplaces, service facilities, and social contacts

Social sustainability
- Creating a better quality of life through more social interaction, community spirit, and cultural vitality due to the proximity to facilities, services, amenities, workplaces, public spaces, public transportation, as well as the opportunity for walking and cycling
- Reducing crime and providing a feeling of safety through natural surveillance
- Improving social equity through better access to services and facilities and flexible design of housing in terms of mixed forms and affordability
- Enhancing social cohesion through a sense of belonging and connectedness
- Supporting human, psychological, and physical health through ready access to open green space, walkability in neighborhoods, and social contact
- Enhancing livability in terms of social stability and cultural and recreational possibilities
- Healing spatial segregation by forging the physical links and bridging barriers between communities

2.4. The compact city paradox

Although research and policy argue for more compact cities, referring to higher density, diversity, mixed land use, sustainable transportation, and green areas, this approach to sustainable urban development is associated with some conflicts and contentions.

To begin with, the compact city model produces high levels of noise pollution due to the close proximity between dwellings, transport lines, business activities, and service facilities (De Roo, 2000). Thus, the concentrated impact of dense populations on the environment and the lack of planning for noise pollution control prevent the desired outcomes of this model from being achieved, e.g., direct negative health effects. Moreover, a number of studies (e.g., Breheny, 1992, 1997; Neuman, 2005) argue that compact urban developments can increase land and dwelling prices, cause severe congestion in transport, and create social exclusion. Also, it is argued that neighborhood density might impact negatively on neighborhood satisfaction (Bramley and Power, 2009), sense of attachment, and the quality of public utilities (Dempsey et al., 2012). Breheny (1997) empirically investigates the effects of the compact policies on the population, and concludes that people are unsatisfied about higher–dense development of dwellings. More dense urban areas are, based on research, often responsible for increasing the levels of crime

(Burton, 2000).

Furthermore, arguing against the concept, critics of the compact city highlight increased ecological footprint due to higher consumption, larger income gaps (Heinonen and Junnila, 2011), unfavorable living conditions for low income groups, and lack of accessibility to green space (Burton, 2001). The first two issues might be linked to low income population in dense urban areas, rather than to how the urban form is designed (Glaeser, 2011). They may also be due to a design problem and not necessarily associated with urban compactness given that crowding is a matter of perception of urban space (Kearney, 2006). Similarly, the negative social issues of density may be attributed to the aspects of the urban areas in terms of poverty concentration, rather than to how the urban form is designed (Bramley and Power, 2009). Accordingly, urban problems and urban form are not clearly correlated. Generic problems of urbanization are riskily criticized as being problems of the compact urban form (Bibri 2020b). As Glaeser (2011, p. 9) puts it: "Cities do not make people poor; they attract poor people. The flow of less advantaged people into cities from Rio to Rotterdam demonstrates urban strength, not weakness."

The debate over the compact city as a set of planning and development strategies is actually between the "decentrists" who are in favor of a decentralised form and the "centrists" who are in favor of a high–densely built form (Bibri, 2020b). Breheny (1996) discusses in more detail the view on the future of urban form in regard to decentrists, centrists, and compromisers. Based on the literature, the main critical arguments of the compact city are advanced by the decentrists who question the environmental benefits delivered by compactness strategies. They claim that the anticipated energy reduction is modest compared to the discomfort inflicted by compactness policies as necessary rigorous measures. They believe that it is impossible to halt the urban decentralization phenomenon that is suited to the majority of the population, which favors the tranquillity of rural and semi–rural areas. In short, the key reason for the heated debate revolves around GHG emissions, energy consumption, and the loss of open green areas in light of the escalating urbanization trend. A key point against the compact city model regards the loss of green spaces in urban areas and the inevitable development of green fields outwards due to high congestion and high density (Breheny, 1996).

As another line of argument, policy makers have been "cherry–picking those aspects of the compact city as a sustainable urban model most attractive to their needs, such as increasing densities and containing urban sprawl …, which largely reflect dominant economic or environmental interests" (Dempsey and Jenks, 2010, p. 119). However, it is also safe to argue that confronting the hegemony of unsustainable economic development takes time as to creating and establishing robust alternatives within urban planning (Hofstad, 2012).

Worth pointing out is that the above conflicting and contentious issues are still largely associated with the whereabouts of the compact city as to its implementation and development. According to Breheny (1997), the conclusions of many studies are pretty vague and vary from case to case when it comes to the environmental benefits delivered from the compaction strategy. Indeed, urban form attracts growing interest as the spatial concretization of urban sustainability (Oliveira and Pinho, 2010). This pertains particularly to those countries with a high level of sustainable development practices. Besides, as planning occurs in an open urban system with many individual and collective actors with different interests, it is difficult to link planning functions to outcomes (at different spatial scales) in the urban reality (Laurian et al., 2010). Nonetheless, there are highly institutionalized planning approaches that can be applied to raise the likelihood that planning affects the urban reality. Lim and Kain (2016) examine the differences in the outcome of different planning systems in Sweden and Japan in relation to dense and diverse development.

Furthermore, compact cities involve a number of problems, issues, and challenges when it comes to planning, design, and development at the technical and policy levels in the context of sustainability. Bibri (2020a) provides a detailed review of the compact city in terms of fallacies, deficiencies, difficulties, uncertainties, as well as new opportunities that are being offered by advanced ICT, especially big data technologies and their novel applications. Indeed, it has been suggested that the compact city needs to embrace and leverage what advanced ICT has to offer so as to improve, advance, and maintain its contribution to sustainability. Bibri (2020b) provides a comprehensive state–of–the–art review of compact urbanism as a set of planning and development practices and strategies, focusing on the three dimensions of sustainability and the significant potential of data-driven solutions and approaches for enhancing compact urbanism under what is labelled "data–driven smart sustainable urbanism."

3. Research methodology

3.1. Case study as an integral part of a backcasting-based futures study

This case study is an integral part of an extensive futures study that is being conducted to analyze, investigate, and develop a novel model for data-driven smart sustainable cities of the future using backcasting as a scholarly and planning approach (Bibri and Krogstie, 2019a, b). Backcasting scenarios are used to explore future uncertainties encountered in society, create opportunities, build capabilities, guide policy actions, and enhance decision–making processes. They allow for new options to be considered reasonable, thereby widening the perception of what could be feasible and realistic in the long-term. The fundamental question of backcasting-based futures studies is: "If we want to attain a certain goal, what strategic actions must be taken to get there?" Accordingly, backcasting starts with defining a desirable future and then works backwards to identify the strategic steps needed to build feasible and logical pathways between states of the future and the present. Developing pathways from this perspective allows to imagine the impacts of alternative scenarios, which are commonly used as a tool for strategic planning, especially in relation to sustainability. Having a strongly normative nature, backcasting is especially well equipped to be applied to sustainability issues (Bibri, 2018c; Dreborg, 1996; Holmberg, 1998; Quist, 2007; Robert et al., 2002).

3.2. Case study research

Case study research has long been of prominence in many disciplinary and interdisciplinary fields. As a research methodology, case study is well established in different academic disciplines. Creswell et al. (2007, p. 245) describe case study methodology as a type of design in qualitative research, an object of study, and a product of the inquiry.The authors conclude with a definition that collates the hallmarks of key approaches and that represents the core features of a case study:"a qualitative approach in which the investigator explores a bounded system (a case) or multiple bounded systems (cases) over time through detailed, in–depth data collection involving multiple sources of information … and reports a case description and case–based themes" (Creswell et al., 2007, p. 245). In particular, case study methodology entails the use of multiple sources of evidence (Yin, 2009, 2017), e.g., documents, observations, interviews, focus groups, and so on. These approaches provide a more synergistic and comprehensive view of the problem under investigation (Flyvbjerg, 2011; Merriam, 2009; Stake, 2006; Yin, 2014, 2017).

3.3. Case study design categories

According to their design, case studies can be divided into several categories, including descriptive, explanatory, exploratory, illustrative, cumulative, and critical instance, each of which is custom selected for use depending on the objectives of the researcher. Case study research can be used to study a range of topics using different approaches for different purposes (Simons, 2009; Stake, 2006; Stewart, 2014; Yin, 2017). With that in mind, this case study uses a descriptive design, an approach which is focused and detailed, and in which questions and propositions about the phenomenon of the compact city are carefully scrutinized and articulated at the outset. The articulation of what is already known about this phenomenon is referred to as a descriptive theory, which in this context pertains to sustainable urban forms. Therefore, the main goal of this descriptive case study is to assess the selected cases in detail and in depth based on that articulation. This research design intends to describe the phenomenon of the compact city in its real–world context(Yin, 2014, 2017). It is worth pointing out that the internal validity in this research design, i.e., the approximate truth about inferences regarding cause-effect in relation to this phenomenon is not relevant as in most descriptive studies. It is rather relevant in studies that attempt to establish a causal relationship such as explanatory case studies. Indeed, descriptive research is used to describe some relevant characteristics of certain phenomena, and does not address questions about why and when these characteristics occured, thereby no causal relationship.

3.4. Descriptive case study characteristics

Descriptive research here involves the description, analysis, and interpretation of the present nature, composition, and processes of two compact cities in Sweden, where the focus is on the prevailing conditions. That is, how these cities behave in the present in terms of what has been realized and the implementation of plans based on the corresponding practices and strategies as associated with compact urbanism. This entails the ongoing and future activities being, and yet to be, undertaken in accordance with the time horizon set in the planning and development documents of the two cities. Moreover, as an urban event based on two instances, the compact city involves a set of indicators of an integrated city system in operation that requires an analysis to allow obtaining a broad and detailed form of knowledge about such system. To achieve this, we adopted an approach that consists of the following steps:

- Using a narrative framework that focuses on the compact city model and its contribution to the three goals of sustainability as a real–world problem, and that provides essential facts about this problem, including relevant background information
- Introducing the reader to key concepts, strategies, practices, and policies relevant to the problem under investigation.
- Discussing benefits, conflicts, and contentions relevant to the problem under investigation.
- Explaining the actual solutions with regard to plans, the processes of implementing them, and the expected outcomes.
- Offering an analysis and evaluation of the chosen solutions and related issues, including strengths, weaknesses, tradeoffs, and lessons learned.

3.5. Descriptive case study as a basis of backcasting

One of the essential requisites for employing case study stems from one's motivation to illuminate a complex phenomenon (Meriam, 2009; Stake, 2006; Yin, 2017). Accordingly, the outcome of this descriptive case study should serve as an input to Step 5 (specifying and merging the components of a new model of urbanism to be analyzed) and Step 6 (performing backward–looking analysis to build this model) of the futures study (Bibri and Krogstie, 2019a, b). By carefully studying any unit of a certain universe, we are in terms of knowing some general aspects of it, at least a perspective that guides and informs subsequent research (Wieviorka, 1992). In other words, descriptive case studies often represent the first scholarly toe in the water in new areas of inquiry. With that in mind, the primary purpose of investigating the cases of Gothenburg and Helsingborg is to identify the compact city strategies that are needed to develop the proposed model for data-driven smart sustainable cities of the future with respect to the first set of its urban components. The second set of its urban components has already been identified through a second case study on the eco-city strategies (see Bibri and Krogstie, 2020a). Similarly, as to its technological components, they have been identified through a third case study on the innovative applied solutions of data-driven smart cities (Bibri and Krogstie 2020b).

One important use of the case study approach in research is planning, which in turn is at the core of the backcasting approach to futures studies. However, the purpose of analyzing and evaluating the two cases considered here together with the other four cases—two eco–cities (Stockholm and Malmö) and two data–driven smart cities (London and Barcelona)—is to provide a foundation for backcasting the future phenomenon of the data-driven smart sustainable city. In this case, it is necessary first and foremost to define which characteristics of the future state of this phenomenon are interesting and meaningful and should hence be included in the backcasting (see Bibri and Krogstie, 2019a, b for Step 1, 2, and 3 of the backcasting study). Evidently, recent data in this regard are of primary importance as a basis for the backcasting endeavor. Other material needed to make the backcasting depends on how strong the "theoretical and disciplinary framework" we have about the expected data-driven smart sustainable city of the future and its internal relationships (see Bibri, 2018a, 2019a, 2020a for further details). Commonly, quite a strong basis for backcasting is available when there is a framework which underpins and explains the phenomenon in question in terms of its foundation, justification, and expected outcomes as a new paradigm of urbanism. All in all, the results of all the case studies carried out are intended to guide and inform the backcasting-oriented futures study as an overarching scholarly endeavor.

3.6. Selection criteria

The selection of all of the cases to be studied was done in line with the overall aim of the backcasting-oriented futures study being carried out. The cases of Gothenburg and Helsingborg have been selected using a theoretical sampling approach (Yin, 1984). The two cities fall within the category of large cities in Sweden (see Table 5). In addition, the ambition and success of these cities in the field of compact urbanism makes their planning practices and development strategies an ideal sample to analyze. This assertion can be demonstrated considering the international positioning of Sweden in urban sustainability. Sweden is one of the leading Scandinavian, European, and Global countries that have exemplary practical initiatives in sustainable cities, both compact cities and eco–cities, in addition to a number of recent endeavors related to smart sustainable cities. According to several rankings, Sweden, Denmark, Finland, Norway, Germany, the Netherlands, and Japan have the highest level of sustainable development practices (Dryzek, 2005). Another ranking has recently been reported based on 2018 Environment Performance Index (EPI) data: Sweden is one of the world's leading countries in sustainability and has an overall score of 80.51 in regard to environmental friendliness (Buder, 2019). In fact, several empirical studies identify from the mid–1980s onward an increasing ecological disruption in most of the ecologically advanced nations, such as Sweden, Denmark, Germany, and the Netherlands (Mol, 2000).

In the context of this paper, the two Swedish cities selected have been receptive to the compact city ideal. They have chosen the compact city model as the most effective planning system that can go hand in hand with sustainable development in light of the relevance and usefulness of the findings produced by many studies in the field of sustainable urbanism. As such, they may be seen as successful examples of compact city planning and development and critical cases in sustainable urban development. This is due to their long planning traditions and the existence of relatively solid economic resources on the local level, the national focus on sustainability in Sweden, and the wide authorization given to the local authorities (Baldersheim and Ståhlberg, 2002; Kalbro et al., 2010; Rose and Ståhlberg, 2005). Moreover, they express sustainability ambitions in their master and comprehensive plans, support progress and expansion over time, and experience developmental pressure on their landscapes due to rapid urban growth. Additionally, it was important to ensure that there was sufficient information available in the public realm to carry out the analysis of the two cases. All in all, the selection criteria secured cases where sustainability discourses, planning measures, practical advances, and future goals are present. Gothenburg and Helsingborg illustrate how ambitious cities handle the challenges of sustainability and urbanization, and how different values and interests are weighted and secured through urban planning and development.

3.7. Unit of analysis and data collection and analysis methods

The focus of the backcasting-oriented futures study constitutes the basis for determining the unit of analysis concerning the cases in question. Accordingly, the object of the study on focus in this paper is the design strategies of the compact city and the extent to which they produce and balance the environmental, economic, and social benefits of sustainability. This is essential to focalizing, framing, and managing data collection and analysis. The qualitative data were extracted from multiple sources of evidence identified with a series of searches performed in various online databases. The relevant archive records and documents produced by public and private organizations were considered as primary sources (i.e., master plans, comprehensive plans, visions, strategies, agendas, project descriptions, etc.). In addition, an amount of data was acquired from other documents produced by organizations or researchers not directly involved in the compact city initiatives of Gothenburg and Helsingborg. These sources were considered as secondary (i.e., reports, newspaper articles, journal and online articles, conference proceedings, research project deliverables, etc.).

Another supporting form of the primary data used was face–to–face and telephone interviews conducted with a total of 10 interviewees, including planners, architects, developers, consultants, and administrative servants, These interviewees were mostly involved in those areas associated with the challenging and conflicting issues of the compact city initiatives. These issues were identified based on the previous empirical studies carried out in relevance to this study as well as on the arguments advanced by the critics of the compact city model in the literature. One of the key objectives of the interviews was to corroborate any progress made by the two cities as to the development and implementation of new measures to address the common environmental and social issues of the compact city.

The interviews were mostly unstructured. They were intended to be used in ways that can be adapted to the interviewees' roles and interests. This means that the interviewees were asked different questions. The findings were reported in a form of complementing, substantiating, and conflicting statements. Additionally, a set of face–to–face and telephone conversations were conducted with some researchers and scholars at Lund University and Gothenburg University. They were particularly important in providing further insights into some ongoing projects for strengthening the influence of the environmental and social goals of sustainability over urban planning and development practices in the context of sustainable cities.

To identify, analyze, interpret, and report the case–based themes, a thematic analysis approach was designed and employed. This qualitative analytical approach was deemed suitable given the form of knowledge and insights that we sought to gain from the qualitative data gathered. Thematic analysis is particularly, albeit not exclusively, associated with the analysis of textual material. Braun and Clarke (2006) suggest that thematic analysis is flexible in terms of research design given that it is not dependent on any particular theory: multiple theories can be applied to this process across a variety of epistemologies. Also, thematic analysis is more appropriate when dealing with a large body of qualitative data. As such, it takes as its analytic object meaning by attending to the content of text in its various forms, while keeping in mind how the data are generated, attending to some form of context for interpretation purposes. This pertains particularly to secondary data. Secondary analysis usually involves some degree of distance from the original data as regards to the research questions and place where the data were gathered (see Elliott et al., 2013 for a discussion).

Thematic analysis is an umbrella term for a variety of different approaches, which are divergent in regard to procedures. Here, we adopted a deductive approach to thematic analysis, which involves handling the data with some preconceived themes that are expected to be reflected in the data based on existing knowledge (descriptive theory).

The main four steps of the analytical approach are as follows:

- Reviewing the multiple sources of the data related to the selected cases. The outcomes of this process are numerous themes that are associated with the compact city model. It is important to have a comprehensive understanding of the content of the documents and multidisciplinary literature and to be familiarized with all aspects of the data collected. This step provides the foundation for the subsequent analysis.
- Pattern recognition (searching for themes) entails the ability to see patterns in seemingly random information. The aim is to note major patterns within the result of the first step. This second step looks for similarities within the sample and codes the results by concepts. Coding involves identifying passages of text that are linked by a common theme allowing to index the text into categories and therefore establish a framework of thematic ideas about it. In this step, the preliminary codes identified are the features of the data that appear meaningful and interesting, and the relevant data extracts are sorted according to the overarching themes. Accordingly, coding facilitates the management of the vast amount of the data that has been collected. It is important to allude to the relationship between codes and themes.
- Revising themes is about combining, separating, refining, or discarding initial themes. Data within the themes should cohere together meaningfully and be clear and identifiable as regards the distinction between these themes. A thematic 'map' is generated from this step. Important to note is that this mapping is informed by the broader concepts of the compact city, namely "compactness," "intensification," "densification," "density," "mixed land use," "diversity," "social mix," "sustainable transport," and "green space," as linked to the goals of sustainability. Subsequently, the theme names are provided with clear working definitions capturing the essence of each theme, as well as highlight the main synergies between the core dimensions of the compact city.
- Producing the report involves transforming the analysis into an interpretable piece of writing by using vivid and compelling data extracts that relate to the overarching themes, research questions, and literature. This is a fundamental step for supporting future comparative research and cross-case analysis (Yin, 1984; Patton, 2012). The report must go beyond a mere description of the preconceived themes and portray an analysis supported with empirical evidence that addresses the research questions.

This analytical strategy has allowed us to analyze the selected cases considering the different perspectives of multiple observers. Moreover, the final description of the process has gained greater strength thanks to the triangulation made possible by the use of multiple sources of evidence (George and Bennett, 2005; Yin, 1984; Voss et al. 2002).

3.8. Brief on the case study cities

Urbanization with its different dimensions is increasingly shaping the urban state of Gothenburg and Helsingborg, Sweden, through population and employment increase and related land use change. These cities are in a phase of expansion with a growing population as a result of increased immigration. Urban planning is seen in these cities as a valuable force to achieve the objectives of sustainable development through compact urbanism as a set of practices and strategies. The two cities are characterized by different levels of compactness and respond differently to its sustainability debate due to the escalating rate of urbanization they are facing. Table 5 provides some key figures about the case study cities.

Table 5
Some key figures about the case study cities.

	Gothenburg	Helsingborg
Land area	447.8 km^2	346 km2
Population	599 000	135 300
City ranking in Sweden by population and size	2nd	7th
Average age	39	40

4. Results: The compact city strategies and their environmental, economic, and social benefits

In the two cities, compact planning and development entails the promotion and creation of densely developed nodes/areas with a mixture of functions and demographics supported by sustainable transportation and green space. These nodes are termed differently and also overlap: "strategic nodes," "compact development," "developed areas," and "intermediate city." Despite this variation of names, they are built on the same design strategies of the compact city. As such, they correspond to the ideal of this model as to the tripartite value of sustainability. We now take a closer look at the two cities' plans and development strategies to identify the key dimensions of the compact city and their link to the goals of sustainability. In this respect, we deem it relevant and useful to include a brief definition of the key design concepts of the compact city.

4.1. Compactness

Generally, compactness suggests efficient land planning, density of the built environment and intensification of its activities, diversity, land–use mix, and sustainable transportation. It is at the core of the Comprehensive Plan for Gothenburg and the Master Plan for Helsingborg with regard to practices through design and development strategies. A denser, more diverse city with a greater mix of uses together with sustainable transportation and green space is what Gothenburg and Helsingborg strive to attain through institutionalized practices by developing and implementing a number of strategies and measures to contribute to the goals of sustainability (Gothenburg City Council, 2009; Helsingborg, 2009a).

As a widely acknowledged strategy for achieving sustainable urban forms, compactness of the built environment also denotes urban contiguity, connectivity, and agglomeration. As such, it suggests that future urban development pertaining to the physical dimension of urbanization (land use change) should take place adjacent to existing urban fabrics and structures. Thus, the potential of the available building zones should be exploited to enable future structural development in the existing urban areas based on inward development strategies. This relates to the intensification of the built form, a major strategy for achieving compactness by means of more efficient land use through the densification of development. This strategy entails developing less or undeveloped urban land, redeveloping previously developed sites and buildings, extensions and additions, conversions and subdivisions (Jenks 2000)—in short, infill, renewal, development, redevelopment, and transformation. The compact city concept is associated with the term "urban intensification," which "relates to the range of processes that make an area more compact" (Williams, Burton and Jenks, 1996a).

Gothenburg City Council (2014a) and Helsingborg (2010a) state that compactness is supported by the need for development strategies because many people want to live and work in the city based on a recent forecast up to 2035 for both cities. An increasing population needs more housing, more workplaces, more services, more facilities, more public transport and squares, and so on. The focus of compactness in the two cities is on concentrated development in the city center and complementary development in and around the strategic nodes. The Comprehensive Plan for Gothenburg and the Master Plan for Helsingborg have a lot in common when it comes to their clear aim for urban development and their growth within the already built–up areas. This implies that the continued planning should focus on supplementing the built–up areas in combination with concentrating on the strategic nodes, meaning building the city from the center outwards.

The compact city is the main strategy used for the planning system of the two cities, and aims at the combination of environmental, economic, and social dimensions towards more sustainable development of the city. As observed in the central renewal areas of Helsingborg, a more compact form is evolving through multiple ongoing development projects, which is expanding the center and making it denser, more accessible, and more attractive. Developing from the center outwards can satisfy demand for business sites and service facilities, and increased densities and shorter travel distances give more people the opportunity to walk or cycle (Helsingborg, 2010a). Around the strategic nodes, the aim is to attain a compact building characterized by the diversity of functions (workplaces, housing, facilities, services, etc.) and demographics (age, gender, ethnicity, status, income, etc.) to make urban environments more vibrant and attractive (Helsingborg, 2010a). The financing of place regeneration is argued by Helsingborg to be a positive side effect of the decision to embrace compact development in the transformation areas. Development in relation to the establishment of businesses and services and new dwellings is highly encouraged, particularly when it targets one of the nodes.

According to the Comprehensive Plan for Gothenburg, different planning strategies are adopted with respect to the staged expansion of the city (Table 6).

All in all, Gothenburg and Helsingborg are pursuing three directions to attain the compact city, namely:

- Develop central and renewal areas
- Make use of what already exists: strategic nodes, intermediate city, etc.
- Focus energy and effort where it will make a difference in the context of compactness.

4.2. High density and its relation to multidimensional mixed-land use

Density is a critical strategy in determining the compact urban form. Urban density refers to the ratio of dwelling units or people to land area. In a recent study, Lim and Kain (2016) investigate five urban areas in

Table 6
Planning strategies for city expansion.

Planning Strategies for City Expansion
• Build and Develop Centrally: A substantial share of future development is planned to take place in the central renewal areas. A more compact city will emerge, making the city's center larger and more attractive and accessible, and a mixture of residents, workers, and visitors will create a stimulating environment that draws in new knowledge and service-based companies. Current plan projections indicate that housing and employment growth can be accommodated within the central renewal areas by strengthening them with 30.000 new homes and 40.000 new jobs by 2020.
• Concentrating on Strategic Nodes: Compact development brings together both functions and people around strategic nodes, creating places that are alive throughout the day. Gothenburg has several strategic nodes in addition to several interchanges where higher densities are being aimed for together with effective accessibilities.
• Complement and Mix: The objective is to complement those areas that both are easy to reach by walking and cycling and have good access to public transport with additional homes and workplaces, leading to greater variety and a more vibrant city by enhancing existing urban structures. New development and re-development are planned to contribute to the increased diversity (social and functional mix) and vitality of the city districts.
• Outer Areas Reserved for Future Consideration: These areas have future potential for the development of diverse homes and workplaces and are required to achieve a certain level of density based on the feasibility of high quality public transport. They share a common need for significant investments in infrastructure and services.

Source: Bibri (2020a).

Gothenburg representing the outcomes of the key strategic planning approaches that have been applied historically in the city. Three indicators for compact city form were used for the assessment of dense and diverse built environments: the density of built objects, the scales of built objects, and the distribution of the diversity of built objects. The assessment was applied to three kinds of planning outcomes (urban fabrics) achieved through three types of planning approaches as follows:

- Emergent compact urban form achieved through planning by coding
- Designed compact urban form achieved through planning by design in combination with planning by development control
- Designed dispersed urban form achieved through planning by design

As regards the findings, concerning the density of built objects, the study showed that in Gothenburg the highest density of 37% and 31% is in type 1, the in–between density of 19% and 14% in type 2, and the lowest density of 12% in type 3. These results pertain to five study areas chosen in Gothenburg according to the applied planning approach: rule–based, with 2 areas in Type 1, 2 areas in Type 2, and 1 area in type 3. With respect to the scale of built objects, building footprints of over 750 m2 consisted of high percentage of all buildings in Gothenburg, namely <1500, >1500, <2250, <3000, >3000. As to the distribution/diversity of building footprints, larger scale buildings were much frequent in Gothenburg for all urban types. Moreover, the results showed increased density and more diversity in areas designed with a density and diversity oriented approach (Type 2). Important to note is that the focus of the study conducted by Lim and Kain (2016) is on the comparison between Gothenburg and Japan.

However, achieving a compact city is not only about increasing density *per se* or across different spatial scales, but also about good planning to achieve an overall more compact urban form. This pertains to the strategic urban development associated with the potential for higher densities through densification. As stated in the Development Strategy Gothenburg 2035, to be able to plan for a long–term development of the city, it is necessary to analyze the potential for greater density in the intermediate city. "This potential is based on the existing housing forecast that extends to 2022. The work shows that there is potential to build a total of 45 000–55 000 homes in the intermediate city. Of this, around 15 000 homes are included in the forecast up to 2022 and 31 000–40 000 homes after 2022… The intermediate city, the inner city and the central renewal areas are expected to be able to contain development volumes of around 2 500–4 000 homes per year" (Gothenburg City Council, 2014a, p. 7). The intermediate city in Gothenburg is the interlinked city area just outside the city center that has good public transport, good services, and where many of the city's inhabitants live and work. It covers a large part of the built–up area and contains buildings and areas with very different characters. Part of the intermediate city are also three of the five key nodes targeted by the development strategy.

The key–node strategy is meant to contain the further expansion of new areas, until the empty spaces left in the inner city and the surrounding nodes are developed. Dense settlements are planned to be developed around strategic hubs that bring together functions and people to create living spaces for many hours of the day. Beside the five main nodes, there are several smaller hubs and interchanges with good accessibility which also pursue the high density. Those areas are characterised by a mix of functions as housing, offices, services, cultural facilities, and recreational areas to achieve a vibrant urban environment, combined with a good access to public transport and good cycle paths linked with the rest of the city, meant to facilitate the mobility of people. On the whole, the aim of the densification strategy is to create high-density nodes in order to implement the use of public transport, reduce the car dependency, and to contain the sprawl.

Similar aspects of strategic urban development in the case of Helsingborg (2010a) are associated with what are locally termed as nodes. These correspond to the geographical zone where most of the people live and more than half of the workplaces can be reached by public transport within less than 1 h, from stop to stop. Indeed, regarding the long–term development of the City of Helsingborg, the potential for greater density is analyzed in regard to the nodes (Helsingborg, 2010a). This potential as based on the existing housing forecast entails the number of houses and villas that are planned to be built each year, which varies from a node to another. The inner city, the central development and redevelopment areas, and the nodes are expected to be able to contain development volumes of varied number of homes per year. Also, a high density is to be sought for in all nodes, and this development will contribute to strengthening the areas' central points and thus to achieve a multidimensional form of mixed-use, i.e., physical land–use mix, economic mix, and social mix. Similarly, a high density is to be aimed for in all prioritized development areas, and this development shall contribute to reinforcing the areas' central points. Density should therefore "be prioritized close to these future central points, as shall supplements to attain a good mix of functions and a good social mix" (Gothenburg City Council, 2014a, p. 33). The multidimensional mixed–use strategy is hand in hand with the high–density strategy.

Urban density is used as a variable in evaluating how livable a city is as to its design. The underlying argument is "that increased population density has a positive effect in several ways for life in the city [Fig. 1], with regard to ecological, social an economic factors. When the built–up city is supplemented with more housing there are more effects that reinforce one another" Gothenburg (2014, p. 16). This relates to the postulation that, at certain densities, generating the interactions needed for the viability of urban functions and activities is determined by the number of people that live within a given area in terms of sufficiency. Following this postulation, Helsingborg aims to secure effective land use through densification and mixed land use within the strategic nodes as well as revitalized city centers with enhanced customer basis and improved transport facilities (Helsingborg, 2010a). Likewise, one important reason for greater density, and thereby creating the possibility for more people to live and work in the diverse parts of the city, is that it gives a larger base for services, retail trade, public transport, and so on Gothenburg (2014a). Therefore, more of mixed uses can become established at more places in the two cities and thus more people will be closer to shops, facilities, bus/tram stops, and so on. Again, there is a clear synergy between density and mixedland use in terms of boosting the environmental, economic, and social benefits of sustainability and their integration.

With regard to the environmental effects of population density, Helsingborg (2010a) argues that the density of built areas and the type of dwellings affect sustainability through the differences in the consumption of resources: energy, materials, and land for housing, transportation, and infrastructure. High density and integrated land use not only conserve resources, but also provide for compactness. However, Helsingborg's plan clearly states that densification and the building of larger entities can impact the noise level and air quality negatively (Helsingborg, 2010a).

Gothenburg's Comprehensible Plan does not make any clear linkage between densification and environmental problems. Nevertheless, in the Development Strategy Gothenburg 2035, the city does take noise pollution levels into consideration when setting restrictions on where densification can occur, as expressed in the following manner:

> "Within several of the prioritized areas as part of the intermediate city noise pollution could be an important condition to consider in planning. At present, the municipality is working on producing a new noise pollution policy. This will be an important base for the continued planning" (Gothenburg City Council, 2014a, p.33).

> "The intermediate city contains buildings and areas with very different characters… When building additional structures, it is important to take into account potential conflicts such as noise pollution" (Gothenburg City Council, 2014a,b, p. 8).

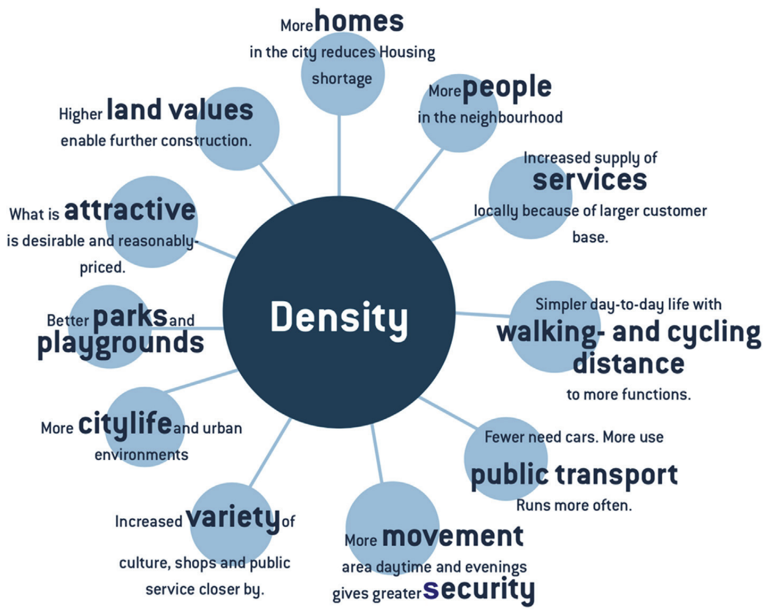

Fig. 1. Multiple positive effects of population density
Source: Gothenburg City Council (2014a).

4.3. Land–use mix and social mix and their relationship to high density

Land use refers to the distribution of functions and activities across space, grouped into different categories. Widely recognized for its important role in achieving sustainable urban forms, land–use mix denotes the diversity and proximity of compatible land uses, a form of cross–sectional residential, commercial, institutional, and cultural infrastructures associated with living, working, and service and amenity provisioning. As a preferred typology in sustainable urban planning and development, diversity, which overlaps with land–use mix as to the variety of land uses, "entails building densities, housing for all income groups through inclusionary zoning, a variety of housing types, job–housing balances, household sizes and structures, cultural diversity, and age groups, thereby epitomizing the socio-cultural context of the urban form." (Bibri, 2019, p. 231) Indeed, diversity has been used interchangeably with social mix (i.e., housing types and options, demographics, lifestyles, etc.) in the literature. The land–use and social mixes are an important part of the planning and development strategies of Gothenburg and Helsingborg, whose goal is to have a more lively and long–run sustainable city with a balance between social, economic, and environmental factors. In fact, the two cities's increasing population and high rate of immigration creates a need for more housing and workplaces. And this diverse population, which moves around in the city and uses public spaces—streets, squares, and parks—makes use of the supply of shops, services, and facilities. There is a clear link between the population growth, residential density, and mixed use. The supply of urban businesses and supermarkets increases with greater population density, and this pertains to the inner city, at a few of the strategic nodes and in local centers close to the inner city (Gothenburg City Council, 2009; Helsingborg, 2010a).

An attractiveness discourse prevails in the two cities, with almost the same intensity. It is mostly linked to land–use mix and social mix in dense areas. Attractiveness in this context is distinguished by a complex mix of uses, the ability to bring people together, as well as the multitude of visual impressions. Creating an attractive and safe city with vibrant life is one of the key aims of the two cities. The compact city model is promoted to provide more attractive and safer streets and districts. Greater compactness gives a city life that attracts more young people and creates a feeling of security (Gothenburg City Council, 2014a). Gothenburg aims to create safe urban areas with a sense of belonging and access to public spaces for meeting opportunities. This can be accomplished by, among other things, designing good public spaces and bridging barriers between different districts. Further, according to the Development Strategy Gothenburg 2035, promoting the mixed–use of functions in the strategic nodes and built–up areas is driven by the attractiveness of the city thanks to the lively areas of the inner–city; moreover, a mixture of functions is associated with proximity in terms of short distances between workplaces, homes, and facilities (Gothenburg City Council, 2014a).

Both attractiveness and safety are intended to be realized by people moving around the city both daytime and evenings—natural surveillance. The mixed land use generates new flows of people and creates opportunities for using places at different times of the day, especially in the evenings when cultural and non–commercial activities are able to supplement the commercial supply. Concerning the economic driving force of the compact city, a mixture of functions, large and diverse population base, short distances, and attractive and secure urban environments, coupled with the proximity to parks and green areas, generate high land values that in turn create a willingness to invest. Indeed, the compact city creates a larger customer base for services, the retail trade, public transport, and so on (Gothenburg City council 2014a). With respect to short distances, access to everyday commodities within a walking distance is a key issue in the future compact and carless City of Gothenburg, which argues that a distance of half of a kilo–meter significantly increases the number of consumers who walk. In addition, there is a clear connection between density and everyday commodities, the local market base is very important to the supply of everyday commodities. As to the density of the built–up areas under redevelopment, making it denser through new construction (supplementation) is motivated by making everyday life easier for inhabitants by enabling them to live closer to shops, leisure, services, and facilities, as well as to reduce the need for transport. Thus, it is necessary to have much greater density. Gothenburg strives after a mix of uses, not only as part of transforming central renewal areas, but also as part of developing strategic nodes, as it enriches the city and makes the surrounding development more attractive to people. Important to note is that the conditions for a mixture of businesses, housing, and activities in Gothenburg relate to what they call a "close–knit city" (Gothenburg City Council, 2014a).

Helsingborg aims to be "Sweden's most attractive city for people and enterprises" (Helsingborg, 2007, p. 2, see also Helsingborg, 2011a). It argues that a mix of housing types and workplaces in the nodes enables a constant flow of people to the city centers, which contributes to improving vitality and safety and providing an environment conducive to human encounters (Helsingborg, 2010a). This is what the city refers to as a 'mixed city' (Helsingborg, 2010a, 2010d). Regarding safety, Helsingborg (2010a) argues that the right mix of features and the right content can produce lively environments even during evenings and weekends, which is important for safety. Furthermore, it contends that the compact city gives greater opportunities to manage daily life on foot, by bike, and by public transport thanks to the proximity to shops, services, facilities, and workplaces. This reduces the needs for long distance transports, as more errands can be run by walking, cycling, or public transport, and more people will have an easier day–to–day life and be more attracted to the city (Helsingborg, 2010a). In addition, Helsingborg claims that a housing mix enables people to live in one area throughout different stages of their life (Helsingborg, 2010a). All in all, the notion of compactness frames and sustains the city's attractiveness ambitions.

Adding to the above is the effort made by the City of Helsingborg to consolidate its position in the regional race to attract young, highly educated people, with the hope that they will create new businesses, including service companies, and provide higher tax revenues. The assumption is that this group wants to be part of an urban environment with a plethora of dwellings, businesses, facilities, services, and amenities with ties to educational institutions. Indeed, people live in the vibrant inner city to enjoy the student life and also the amusement and proximity that the city center offers to them.This applies to Gothenburg as well. A new class is now part of the Gothenburg's community: "creative class," which is a symptom of the changes that have taken place over the last decade in Sweden. One planner from the Municipality of Gothenburg stated, "the creative class is represented by those that chose to settle down in the city center as a living-strategy to avoid using cars to go to work so as to save money and time on the commuting and spend more free time at home with the family or for personal interests. In fact, the high-ways are so crowded and stressful to use, which influenced people to decide to live in the city center." As a token of this, different interviewees from both municipalities asserted to live in the center and to walk, cycle, or use public transport to go to work. They also claimed that the majority of their friends and colleagues live in the city center or the inner city. Further efforts are being made to, as claimed by one interviewee, to build an attractive and safe city center, supported by good facilities, services, amenities, and accessible transportation in order to set up the mind of those citizens that still prefer the countryside life-style in a more sustainable direction.

Regarding the segregation issue, the strategy concerns the enlargement of the core of the city to combine different interest-groups that have the centre as a common public space/meeting point. The aim is to make people integrate in the city centre frst, and then try to mix them in the same living areas, by expanding the attractive core.

Regarding social segregation, a number of residential areas and districts in Helsingborg have been segregated in relation to socio-economic status (Helsingborg, 2009a). As observed in several areas of Helsingborg, there is a division into "immigrant" and "native Swedish" populations, coupled with the persistent socio–economic segregation, which is highly problematic. Similarly, Gothenburg has been segregated in several aspects, the different parts of the city differ substantially, and there is an increasing tendency for socio-economic disparities (Gothenburg City Council, 2014a). Problem areas pertain to the city districts associated with the Million Program, which are ridden with segregation as a problematic issue (Lilja and Pemer, 2010). Hence, the two cities' visions and planning policies promote dense, diverse, and mixed use patterns to reduce socio–economic segregation and increase livability (Gothenburg City Council 2012, 2014a; Helsingborg, 2009a, 2010a). As visible in the Master Plan for Helsingborg, compact city development is seen as a solution for reducing segregation, increased integration, and enhanced diversity, as well as a means of creating identity (Helsingborg, 2010a). Helsingborg focuses even on eliminating what they call "outsiderness," and the aim is to lift communities with low socio–economic status and decrease unemployment and less qualified people (Helsingborg, 2009a).

By the same token, as stated in the Development Strategy Gothenburg 2035, one way of evening out existing socio-economic differences is to ensure that all parts of the city have good physical links, and new buildings are being used to create and achieve these links (Gothenburg City Council, 2014a). The whole development strategy revolves around developing the intermediate city for a closely connected city using the physical planning as a tool. Additionally, Gothenburg is increasing housing in many areas with insufficient services and shops to attract the population and thus provide conditions for establishing more services in different areas. This contributes to a city that is more closely connected, and where the physical environments of the different districts will give the inhabitants more equal conditions. The mixed–use strategy is used in Gothenburg to promote and obtain social mix as to cultural and socio-economic diversity. One architect from the Municipality of Gothenburg confirmed that the problem of social segregation is mainly caused by the desire of immigrants and people from the same class and/or ethnic group to live in the same areas, thereby avoiding to get mixed with people from other background and socio-economic status. The integration between "immigrant" and "native Swedish" populations proceeds slowly, and the quality of urban life in these areas is less than that in the Million Program areas (Gothenburg City Council, 2013). As a response to these issues, Gothenburg has adopted a strategy based on multi–stakeholder involvement, e.g., by making use of diverse firms to develop new urban areas with a mixture of housing and functions (Gothenburg City Council, 2011, 2012, 2014a,b). As to the segregation issue, the strategy adopted concerns the enlargement of the core of the city to combine different interest-groups that have the centre as a common public space. The aim is to make people integrate in the city centre first, and then try to mix them in the same living areas by expanding the attractive core.

In the two cities, the business areas associated with the activities that are incompatible with housing development, e.g., wholesale retailing, industrial facilities, and port activities, are prioritized with specific transport needs, safeguard good access, and no new housing development. Speaking of the economy, there are different institutional practices used to support economic sustainability in Gothenburg and Helsingborg. Based on the document analysis and interviews, the following institutional practices have been identified in the two cities (Gothenburg City Council, 2009, 2011, 2014a, b; Helsingborg, 2009b, 2011a, 2011b):

- Regional collaboration as a measure to enhance business development.
- Strategic business development plans to guide business and tourist development.
- Arenas where politicians, business actors, and public servants meet to discuss topical questions.
- Collaboration and contact with business actors to enhance knowledge and expertise sharing
- Higher educational institutions doing and integrating research into business development as part of academia and industry collaboration.
- Initiatives for developing competencies in a number of business development areas in relation to sustainability by conducting seminars to improve the level of technological knowledge in this regard.
- Innovation labs for enabling interaction and cooperation between scholars, industry experts, business professionals, and thought leaders

to enhance research opportunities, real-world problem solving, and knowledge creation and dissemination.
- Collaborative projects with other cities in the region and across Scandinavia more generally.

4.4. Sustainable transportation

The term "sustainable transportation" is defined as "transportation services that reflect the full social and environmental costs of their provision; that respect carrying capacity; and that balance the needs for mobility and safety with the needs for access, environmental quality, and neighborhood livability" (Jordan and Horan, 1997, p. 72). It is a major strategy for achieving sustainable urban forms. Indeed, it is by relying on sustainable transportation that the dense, diverse, and mixed–use patterns characterizing the compact city enable it to secure environmentally sound, economically viable, and socially beneficial development. As a key component of sustainable transportation, the public transport system involves both the physical infrastructure as well as the level and quality of services provided to citizens. In Gothenburg and Helsingborg, public transport is seen as a key driving factor for reaching a more sustainable city. In addition, mobility management in the two cities is a kind of a soft measure adopted by the public transport authority to make the existing infrastructure more efficient and effective. This authority is responsible for building, developing, and maintaining the different parts of the urban transport infrastructure, and also creates and keeps the dialogue with businesses, universities, and citizens as to how they should make the choice of travel modes for the everyday needs and what can be done to make travel behavior more sustainable (Bibri, 2020a).

The Comprehensive Plan and Master Plan for the two cities emphasize the important relationship between urban planning and development and sustainable transportation. Both cities aim to improve sustainable transportation through new development in the strategic nodes. These are to be located in proximity to railway stations and to be based on mixed land use development that allows for sustainable mobility, such as cycling, walking, and public transport. One of the objectives of Gothenburg and Helsingborg is to put good public transport in place before new areas are developed. The strategic nodes and the built–up areas have already high quality public transport. Moreover, the two cities argue that to achieve an attractive city requires increasing accessibility through enhancing the transport infrastructure. This is planned by the creation of new links, enhancing existing networks, and building new footpaths and cycle tracks in the strategic nodes concerned with concentrated development. The goal of the two cities is to create an effective sustainable community that has good accessibility and safe traffic through urban form and transport infrastructure.

The K2020 project (Fig. 2) in Gothenburg aims to dramatically increase travel by public transport, which requires new public transport infrastructure (Gothenburg City Council, 2009, 2014b). Specifically, as a long–term strategy for public transport in the Gothenburg Region, this project aims to increase the use of collective modes by 2025, from 25% to 40% (1 million trips per day instead of 450.000). Fig. 3 shows the main principles from K2020.

The transport strategy in Gothenburg for a close–knit city indicates how the transport system needs to be developed as more people live, work, shop, study, and meet in the city, that is, in relation to density and mixed land uses (Gothenburg City Council, 2014b).

Helsingborg emphasizes that compact urban development should be appropriate to efficient public transport, walking, and cycling, which are in turn associated with the close proximity to shops, workplaces, services, and facilities in dense areas (Helsingborg, 2010a). Further, as clearly stated in the Guide to Helsingborg 2035, distances are short and public transport is pioneering, and the city has sustainable transport systems (Bibri, 2020a). As regards the advantages of sustainable transportation, it operates the transport system at maximum efficiency, provides favorable conditions for energy–efficient forms of transport, limits CO2 emissions, allows equitable accessibility to services and facilities, promotes renewable energy sources, decreases travel needs and costs, minimizes land use, and supports a vibrant economy (Gothenburg City Council, 2009, 2014a; Helsingborg, 2010a). These benefits can be realized within the framework of the compact city as a set of planning practices and development strategies.

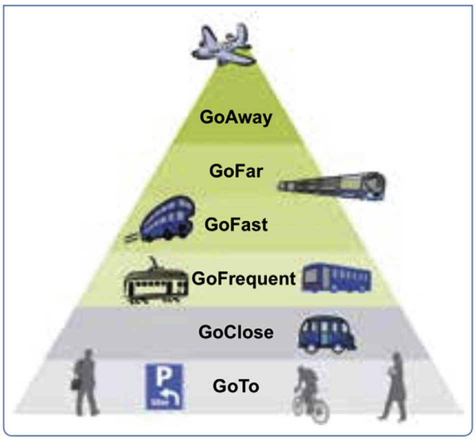

Fig. 2. The K2020 strategy.
Source: Gothenburg 2035 Transport Strategy for a Close-Knit City (Gothenburg City Council 2014b).

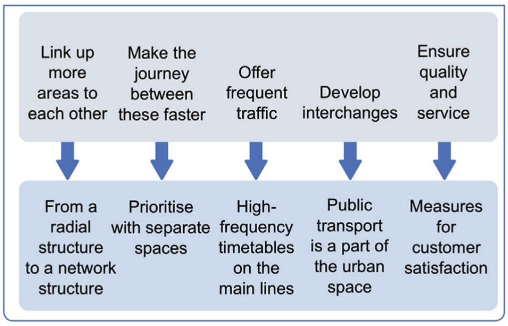

Fig. 3. The main principles from K2020

4.5. Green structure: green space

Greening is a key design concept for sustainable urban forms. Green space can be defined as the areas of nature found in the urban landscape. It includes trees, grassy patches, water features, flowerbeds, and rock gardens. The Municipalities of Gothenburg and Helsingborg adopt the concept "green structure" in planning. This concept constitutes larger green areas, waterways and streams, shorelines, parks, agricultural land, and natural areas as one common structure (Helsingborg, 1995; 2010a; Gothenburg City Council, 2009, 2014a). Green structure plans emphasize the benefits and losses of green and natural areas.

In the two cities, green space relates particularly to health and recreation for a better quality of life. Gothenburg and Helsingborg will be healthy and able to offer good opportunities for recreation (Gothenburg City Council, 2009; Helsingborg, 2010a). They pursue public health plans (Gothenburg City Council, 2009; Helsingborg, 2010d) and have also attempted to secure a linkage between urban planning and public health goals by developing procedures for the purpose. "Access to greenery, sports, and play … shall increase… Planning must have regard to public health" (Gothenburg City Council, 2009, p. 7). In the areas studied in Gothenburg by Lim and Kain (2016), there are larger green spaces and parks in emergent compact urban form. The environmental quality is one of the aims that are of particular relevance to urban planning due to the employed monitoring: ability to enhance the air quality, noise level, and the protection of green areas (Helsingborg 2010d). The issue of air quality can be seen to be keeping pace with the goals formulated. Helsingborg (2010a) promotes the creation of green spaces in the city. One planner from Helsingborg Municipality said, "When people move around in the city, they like to use parks and squares with green features, while green space is highly appreciated in high residential densities. So it is a matter of what people perceive the city life to be and what attracts them to live in it." Nonetheless, there is more to green space than just health and recreation. Greening ameliorates the physical urban environment by removing CO2 emissions and other toxins from the air, enhances the aesthetics of urban areas and thus make them more pleasant, enhances the urban image and increases economic attractiveness, and helps to control storm runoff (Bibri, 2020a, b). For example, as argued by Gothenburg, "proximity to parks and green areas generates high land values that in turn create a willingness to invest" (Gothenburg City Council, 2014a, p.16).

The protection of large natural, agricultural, and cultural areas is a perceived outcome of the compact city model in both cities. "To use land resources effectively means … that we have more space left; space for more houses, more green space, businesses, and services that create added value for the areas in question. By prioritizing development in station–nodes the remaining parts of the countryside with high–class agricultural land or important natural or cultural values can be left unexploited" (Helsingborg, 2010a, p. 14). One planner from Gothenburg Municipality said: "We protect natural and cultural landscapes and agricultural areas by setting long–term limits for dense areas, and by the densification of the nodes and the transformation of the existing developed areas. New homes will be built in these areas to avoid the fragmentation of the large natural, agricultural, and recreational areas." As regards the outer and nature areas, the objective is to "have regard to valuable natural and cultural heritage" and to "protect and enhance natural, cultural, and recreational values" (Gothenburg City Council, 2014a, p. 9). On the whole, the two cities perceive densification and transformation as a means to secure the protection of the valuable areas in question beyond the developed and redeveloped areas. They are also clear on the restriction on the development outside these areas—unless there are economic priorities which could enable the green field to give space at the new suburban infrastructure for wholesale retailing, industrial facilities, and large–scale businesses.

Limiting outward urban expansion should be combined with not only more efficient use of land resources through densification and transformation, but also with more effective measures to protect the green areas within the city. Compactness is about ensuring that we make the fullest use of the urbanized land before taking green fields. However, the future of green areas within the strategic nodes is more uncertain. Particularly if green areas are located in the vicinity of a railway node, they risk being used as building ground (Helsingborg, 2010b). While Helsingborg envisions that it will create "more green areas" (Helsingborg, 2010a, p. 14) and "increase the efficiency of green area usage" (Helsingborg, 2010a, p. 30), it is less specific in regard to the green areas located within the strategic nodes. Gothenburg is relatively more explicit about the relationship between green areas and densification. "Both densification and green areas provide good conditions for a variety of qualities: play areas, close to shops, walking areas, public transport, and so on" (Gothenburg City Council, 2014a,b, p. 51). The city argues for the importance of green space as a design feature in a denser city, and all developments and redevelopments should be designed in ways that minimize their impacts on the environment, i.e., valuable green structure is maintained (Gothenburg City Council, 2014a). However, according to Lim and Kain (2016), larger parks in emergent compact urban form in Gothenburg are distributed less evenly. In view of the above, the main question to raise is to what extent the practices capable of relieving the tension between densification and transformation and the protection of green areas from damage or harm with appropriate measures are detectable in the two cities.

Regardless, green structure plans map the two cities' green resources by assessing their natural and recreational qualities (Gothenburg City Council, 2009; Helsingborg, 2010c). Accordingly, "[l]osses of nature, cultural, or recreation values will be compensated for" (Gothenburg City Council, 2009, p. 7). In the case of densification, "the balance between different interests becomes more difficult, and conflicts of interest must be dealt with at the planning stage of the growing city… It is not possible to avoid values sometimes being lost, but in these cases one needs to compensate for them with new or reinforced values, so the final result is more valuable" (Gothenburg City Council, 2014a, p.16). Helsingborg implements what is called the "balancing principle," a practice which involves a compensation for loss of green areas (Helsingborg, 2010c). Such principle entails an in–depth analysis of the area as a basis for decision–making pertaining to urban development. Although there are no guidelines for what actually functions as to the compensation procedure and what to accept and not in terms of the potential damage or harm to the ecological and natural values, the purpose of such analysis, the value assessment, is to increase the cost of altering the status of the area, of which the value is to be decided through negotiations among the involved stakeholders case by case. Generally, the relationship between urban planning and design interventions and sustainability objectives is a subject of much debate. This means that realizing a compact city requires making countless decisions about urban form, design, and governance, which usually involves complex negotiations and often conflicts. In this regard, one local planner from Helsingborg Municipality said, expressing his concern: "there is weak ground in the balancing principle in that it may be exploited by developers for their own interests by acquiring the right to access green areas for further development." As confirmed by Hofstad (2012, p. 13), "The balancing principle may function as a clause that ransoms developmental interests… Such an alteration of the logic that guides the governing of these areas may make it possible for developmental interests to effectively buy themselves out of this general aim to secure accessible green areas in the city center." In line with this, as stated in the Development Strategy Gothenburg 2035, "[t]here are conflicts of interest in a compact city, but … it is possible to attain … both a green and compact city… When building additional structures, it is important to take into account potential conflicts such as … access to green areas and risk issues" (Gothenburg City Council, 2014a, pp. 6, 8).

4.6. Summary of the results

Table 7 Provides a summary of the results in terms of the core strategies of the compact city for achieving the goals of sustainability.

5. Discussion

The findings showed that compactness, density, diversity, mixed land use, sustainable transportation, and green space are the core design strategies of compact city planning and development as practiced by the two Swedish cities. This is in line with the literature on compact cities in the most essential respects. However, these cities tend to exhibit some differences in the way they develop and implement the compact city strategies to the built form. This is due to their specific physical, geographical, socio–political, economic, and historical aspects. This is consisted with the findings from other case studies on compact cities (e.g., Bibri, 2020b; Hofstad, 2012; Lim and Kain, 2016). Besides, there are great differences between cities in regard to their form (Bibri, 2019a; Van Bueren et al., 2011). Therefore, it is important for cities to make the best use of their local opportunities and capabilities as well as to assess their potentials and constraints from a more integrated perspective when it comes to compact city planning and development. Nonetheless, there

Table 7
Compact city strategies for achieving the goals of sustainability.

Design Principles	Compact City Strategies for Environmental, Economic, and Social Sustainability
Compactness	• Build and develop centrally • Concentrate on strategic nodes • Complement and mix • Strengthen public transport • Reserve outer city areas for future development
Density	• High density of built objects in designed and emergent compact urban form • Diverse scales of built objects • Distribution of building footprints with frequent larger buildings • Greater density in strategic nodes • Prioritization of density close to the central points of strategic nodes • High–density hand in hand with multidimensional mixed land use
Mixed Land Use	• Physical land use mix (horizontal/spread of facilities, vertical mix of uses, amenity, public space, etc.) • Economic mix (business activity, production, consumption, etc.) • Social mix (housing, demography, lifestyles, visitors, etc.) • Greater mix of housing, business, and facilities in strategic nodes • Multidimensional mixed land use hand in hand with sustainable transportation
Sustainable Transportation	• Cycling and walking • Public transport (metro, buses, tram, etc.) • Mobility management • Increased accessibility through public transport infrastructure improvements • Sustainable transportation hand in hand with multidimensional mixed land use and high density • Network structure of link areas to connect the major nodes of the transport system • Separate lanes for the public transport for faster journey time and a punctual and reliable system • More services along the main corridors for greater frequency • An easy to understand, safe, and secure system for guaranteeing quality and service • Multi-model travelling in strategic nodes to support their dense, mixed use central points
Green Structure	• Green areas and parks • Green areas hand in hand with density • Protection and integration of natural, agricultural, and cultural areas through intensification
Intensification	• Increase in population • Increase in redevelopment of previously developed sites, subdivisions and conversions, and additions and extensions • Increase in development of previously undeveloped urban land and buildings • Increase in density and diversity of sub-centers • Investment in and improvement of transport infrastructure and services

are no striking or conspicuous differences between the two cities as to the applications of the theoretical underpinnings of the compact city to the built environment—the way the compact city model is practiced and justified in compact urbanism, just as with many cities across the world as illustrated in Table 2. Especially, both cities are located in Sweden as one of the leading countries in the practice of sustainable development, and where relatively similar land use, institutional, environmental, economic, and social policies are adopted by most of, if not all, the city governments.

In addition, at the core of the compact city model is the clear synergy between the underlying design strategies in terms of their cooperation to produce combined effects greater than the sum of their separate effects with regard to the benefits of sustainability in regard to its tripartite composition. For example, urban greening enhances the presence of the compact ideas in the urban areas that are targeted by densification and transformation strategies. Also, the availability and quality of the public transport infrastructure is a determinant factor for stimulating urban development projects pertaining to compactness in the strategic nodes as well as the built–up areas so as to boost the benefits of sustainability. In general, urban development policies are supported by the advocates of the agglomeration effects (Glaeser, 2011) made by the proximity, contiguity, and connectivity of diverse urban components. This results in a more environmentally sound, economically viable, and socially beneficial form of development through dense, diversified, and highly integrated patterns that rely on sustainable transportation and favor green space (Bibri and Krogstie, 2020c).

Furthermore, the findings showed that the compact city model as practiced by the two cities is justified by its ability to contribute to the environmental, economic, and social goals of sustainability. This corresponds to the results obtained from other studies (e.g., Bibri, 2020b; Hofstad, 2012). In fact, the centrality of the compact city ideal and especially its three sustainability dimensions in urban planning and development is found throughout the western world (Easthope and Randolph, 2009; Healey, 2002; Portney, 2002; Raman, 2009; Vallance et al., 2005). The measures of the compact city provide a series of environmental, economic, and social benefits as they are designed to revitalise existing city areas, increase walking and cycling, enhance the use of public transportation, and preserve recreational and open green space (Jenks and Jones, 2010). The compact city model provides better economic outcome (Quigley, 1998), reduces energy consumption and pollution through densification (Breheny, 1995; Mindali et al., 2004), and alleviates social segregation (Burton, 2001).

Concerning environmental sustainability, the two cities aim to decrease travel needs and thus mitigate GHG emissions through walking, cycling, and public transport; to reduce the pressure on green and natural areas; and to conserve energy through building densities that support combined heat and power systems. Cities as the most compact settlements of people have a tremendous effect on environmental changes (Girardet and Schumacher, 1999), and low population density is the most environmentally harmful form in urban structures (UN–Habitat 2014b). In particular, the planning discourse in the two cities correlate with the compact city ideal as regards sustainable travel. This is at the core of the densification and intensification strategies adopted by the two cities. The main environmental aspects identified, namely sustainable travel and land efficiency, constitute a central part of planning and development practices in both Copenhagen and Oslo (Næss et al., 2011). Newman and Kenworthy (1999) substantiate that the compact urban form involves a less use of energy and a high use of public transportation. In relation to this, most of the public transportation uses electricity to operate, and when electricity is generated by renewable energy (i.e., solar, biofuel, wind, etc), the reduction of emissions can be very significant. The issue of transport dominates the environmental debates on the form of the city (e.g., Bibri, 2020a, b; Bibri and Krogstie, 2017b; Jabareen, 2006; Jenks, Burton and Williams, 1996a). Overall, the intensification of the built form leads to cities which are better suited to sustainable mobility and to energy saving in public transports and district heating (Elkin et al., 1991).

Moreover, the two cities promote green space by means of institutional practices related to green structure. Also, they share the research view that it is possible to attain a city that is both compact and green. The green areas targeted by the strategies of urban development have enhanced the presence of the idea of compactness through the discourse and institutionalization of green structure and the balancing principle and other planning tools applied in Sweden. Especially, natural areas in the two cities are regarded as valuable recreational facilities and a way of making the city more healthy and vibrant, in addition to contributing to the protection of biodiversity and ecosystem services. The health advantages of urban green space tend to be more on focus in research (De Vries et al., 2003; Maas et al., 2006). Green space contributes positively to the objectives of sustainable development in urban areas (Swanwick et al., 2003). New approaches to urbanism need to incorporate ecological thinking in the forms of human settlement (Beatley, 2000). However, green space is a subject of debate due primarily to the core conception of the compact city. In this respect, the argument that the compact urban form has the ability to reduce the pressure on green areas, ecosystem services, and biodiversity remains less certain. While the goal of protecting open green space outside development areas or strategic nodes finds support in the two cities as manifested in densification and expansion projects, it is not certain when it comes to green areas located in or close to the urban fabric given the potential enticing opportunities offered by new urban development projects to further strengthen the economic goals of sustainability, which indeed is the dominant aspect of the compact city initiatives.

It is worth noting that greening as a key dimension of ecological design is typically associated with the concept of the eco–city, another prevailing model of sustainable urban form. Greening and passive solar design are the key distinctive design strategies adopted by a number of approaches to the eco-city (e.g., environmental city, green city, sustainable city, sustainable neighborhood, sustainable urban living, living machines, and garden city (Bibri and Krogstie, 2020a). Passive solar design entails decreasing the demand for energy by using solar passive energy sustainably through the design measures applied to buildings and urban densities. However, this strategy is not mentioned in the planning and development documentation of the two cities and hence not on focus within the framework of the compact city, despite the intensification of the development and redevelopment projects going on in these cities with respect to densification and transformation. The orientation of buildings and spatial patterns of densities environmentally affects the built form (e.g., Jabareen, 2006; Thomas, 2003). A large body of research has demonstrated and discussed the environmental benefits of passive solar design, notably building heat gains and losses, warming and cooling pressures, heat storage and discharge, emissivity, and air and noise pollution reduction (Bibri, 2020b; Bibri and Krogstie, 2020a).

Another design strategy of the eco–city that is also of high pertinence to the compact city as regards to its environmental health, though missing in the two cities' planning and development documents, is "smart urban metabolism" (e.g., Shahrokni, Lazarevic and Brandt, 2015; Shahrokni et al., 2015) and sustainable systems. As argued by Marcotullio (2007), sustainable systems are a key innovation that the compact city needs to adopt because they create the infrastructure to naturally process sewage waste, grey water, and storm runoff on–site, in addition to preventing flooding on the urban hardscape and utilizing wastewater to fertilize and water gardens. Sustainable systems are commonly associated with the eco-city model (Bibri, 2020b; Roseland, 1997). Nonetheless, there are many overlaps among sustainable urban forms in their ideas and concepts, especially the eco-city and the compact city.While these forms are compatible and not mutually exclusive, they involve some distinctive concepts and key differences (see, e.g., Bibri, 2019a, 2020a; Farr, 2008; Harvey, 2011; Jabareen, 2006; Roseland, 1997). For example, the two models share mixed land use, with the difference being that this strategy in the eco–city model is not hand in hand with, or strongly linked to, the high–density strategy as in the compact city model (Bibri and Krogstie, 2020a). Moreover, the mixed–use strategy as applied to the compact city involves four dimensions: the social mix, the physical land use mix, the temporal mix of social and physical issues, and the economic mix (Evans and Foord, 2007).

With respect to economic sustainability, the two cities aim to revitalize the city centers through the promotion of densely built dwellings, businesses, facilities, and accessible transportation; to create proximity between people and their workplaces, thus making sustainable travel possible; to promote greater diversity among employers and job possibilities; and to improve public transportation infrastructure. This finding is consistent with the results obtained from several studies (e.g., Hofstad, 2012; Jenks and Jones, 2010; OECD, 2012b). Additionally, economic development is found to be a significant force in bringing about densification in studies undertaken in Denmark and Norway (Mace et al., 2010; Næss et al., 2011). Important to highlight moreover is that proximity, how close jobs, facilities, amenities, and services are to where people live as generally calculated based on the travel time and distance to their homes, adds another dimension to the compact city: self–sustaining. This means that the city has everything that people need within the community, including stores, employers, service providers, energy generation, waste disposal and processing, and small–scale agricultural production (community gardens and/or vertical gardening) (Li, Wen and Yue, 2016). Again, the latter is typically associated with the concept of the eco–city (Harvey, 2011; Roseland, 1997).

As regards social sustainability, the two cities tie its goals to densification together with social, physical land use, and economic mixes. They aim to improve social equity, social inclusion, social capital, and social cohesion, as well as the quality of life through social interaction, safety by means of natural surveillance, and ready access to services and facilities and green space and recreational areas. Compactness promotes the fairness of the distribution of resources, reducing the gap between the advantaged and the disadvantaged (Burton, 2001), as well as social inclusion, social capital, and social cohesion (Jones et al., 2010; Bramley et al., 2010). One of the arguments that supports social equity is the possibility to have a better access to services and facilities (Burton, 2000). Also, there is evidence that compactness promotes social equity through the reduction of social segregation (Burton, 2001) and spatial segregation by means of flexible design of housing in terms of affordability and mixed forms as well as forging the links between communities (Bibri and Krogstie, 2020a). With respect to the quality of life, the two cities' aims highlight the development of an amalgam of dwellings, businesses, shops, and facilities that makes daily life simpler and life–long living possible and creates vital city centers and public spaces for a healthy, vibrant, diverse, and safe city. Mixed use development promotes vitality, diversity, and safety thereby providing significant social benefits (Arbury, 2005; Bibri, 2020a). Currently, the two cities are facing some challenges pertaining to the institutionalization of planning practices capable of improving the goals of social sustainability. The main problems they are struggling with in their endeavor of achieving the status of the compact city are socio–economic disparity and social inequality.

In light of the above, the perceived positive outcomes of the compact city as related to the two cities' plans are broadly associated with the economic, environmental, and social goals of sustainability. However, it can be observed that the three goals identified tend to have unequal position within the compact city. Specifically, it becomes apparent that the economic goals dominate over the environmental and social goals as supported by the underlying design strategies of the compact city. This is in line with the empirical material pertaining to Helsingborg and Gothenburg. The environmental and social goals are not as intrinsically central to the compact city model as the economic goals, thereby the translation of the latter into concrete measures and hegemonic projects and their institutionalization in urban planning and development practices.

Nonetheless, regarding the environmental goals of sustainability, the common ideals of the compact city model: sustainable transportation and the safeguarding of green areas have been institutionalized through the materialization of concrete measures and projects. Urban green qualities are of particular focus in this regard in light of the practice of green structure plans and the introduction of the balancing principle in Helsingborg. Especially, recent studies suggest that the developments pertaining to the compact city are not as green as promised. As far as the social goals of sustainability are concerned, their translation into concrete measures is still slow and their institutionalisation is facing challenges. It is clear that social sustainability has not yet gained full recognition in Gothenburg and Helsingborg, particularly in relation to social equity and social inclusion. Social proposals in this regard seem to be couched in speculative language in terms of investments, ventures, and employments. This in turn means that social sustainability still lacks concrete or strategic guidelines so as to be, as a vision, converted into concrete measures and projects. The assumption underlying social sustainability is that urban forms cannot be sustainable if they are unacceptable to people and communities.

In sum, the empirical data show the contours of a goal hierarchy between the three goals of sustainability in compact city planning and development. Economic and some eavronemtnal concerns are at the top of the goal hierarchy. This is consistent with the conclusion drawn by Hofstad (2012) that the economic goals remain at the core of planning, while the environmental and social goals play second fiddle. Nevertheless, the compact city model has the ability to respond to different socio–economic and environmental challenges. Therefore, new measures are being developed and implemented by the two cities to strengthen the influence of the environmental and social goals over urban planning and development practices towards balancing the three goals of sustainability.

Compact city development should enable to develop a coordinated, institutional framework to make the most of the opportunities offered by the concept of sustainable development. Perhaps most importantly, the citizens should be given a chance to have a voice in the future of the place where they live. Attractiveness does not depend on economic prosperity alone. Rather, to attract people and enhance livability requires a broader agenda entailing a balanced mix of social, environmental, and economic considerations. And for the two cities to fully achieve the ultimate goal of becoming exemplary models of the compact city, the social and environmental goals of sustainability need to be further supported through institutional practices and thus concrete projects. These involve socially-oriented projects that have high environmental performances and reduce social inequality and segregation (see Bibri and Krogstie 2020a).

Regardless, it is inadequate to focus solely on the form of the city in order to achieve and balance between the three goals of sustainability in an increasingly urbanized world. Monitoring, understanding, and analyzing the processes of urban life (living, building, consuming, producing, etc.) as processual outcomes of urbanization require more innovative solutions and sophisticated approaches in order to advance sustainability. In fact, the form of the city as an outcome of evolution emerges from these processes, not only does it shape them as a structure. However, it is of high pertinence and significance to develop and apply more innovative solutions and sophisticated approaches to deal with the challenges of sustainability and to mitigate the effects of urbanization by incorporating them in urban planning, management, and operational functioning. This is due to the dynamic, synergistic, substantive, and disruptive effects of advanced technologies. New circumstances require new responses with respect to sustainable (compact) urbanism and what it involves in terms of wicked problems. Especially, to tackle such problems requires new technology research and development combined with implementation in practice, and the interdisciplinary research alone remains inadequate (Bibri, 2020b).

Worth pointing out is that sustainable cities are complex systems par excellence and thus dynamically changing, adaptive, and evolving; self–organizing social networks enabled by infrastructure, services, and activities; and developed by multitudinous collective and individual decisions from top–down and bottom–up. Therefore, the emerging computational and scientific approaches, especially those enabled by big data analytics, are of high relevance and importance for understanding and dealing with urban complexities (e.g., Batty et al., 2012; Bibri, 2018a,b, 2019a, e, 2020a, b; Bibri et al., 2020; Betterncourt, 2014; Giannotti et al., 2011). And together with socio-political frameworks and solutions, citizen participation and engagement, and deliberative democracy and behavior of agents (Bibri, 2019d; Greenfield, 2013; Kitchin, 2014, 2016; Kitchin et al., 2015), they should play a pivotal role in solving some of the special conundrums, wicked problems, and intractable issues the contemporary city inherently embodies. In addition, Bibri and Krogstie (2020b) investigate how the emerging data-driven smart city is being practiced and justified in terms of the development and implementation of its innovative applied solutions for sustainability. The authors conclude that the data-driven technologies are being highly developed and increasingly implemented in various urban systems and domains with respect to environmental and social sustainability. This can add a great value to the balance that the compact city is seeking to achieve with regard to strengthening the influence of the environmental and social goals of sustainability over urban planning and development practices. In this regard, different data-oriented competences can be developed and implemented to strengthen the readiness of the compact city to adopt the relevant data-driven solutions and approaches to advance environmental and social sustainability. They include the ICT infrastructure, data sources, horizontal information platforms, operations centers, dashboards, training programs and educational institutes, innovation labs, research centers, and strategic planning offices.

6. Conclusion

Global and local policies on urban planning and development promote the concept of the compact city as a response to environmental integration, economic development, and social justice. The Cities of Gothenburg and Helsingborg should be viewed as successful initiatives in compact city planning and development, on nationaland international scales. This study has been carried as a demonstration endeavor of what these cities are renowned for in this regard, with the aim of being exposed to both local and general lessons. Most of their practices, strategies, and resulting actions are equally relevant to other cities in the developed world.

This paper examined how the compact city model is practiced and justified in city planning and development with respect to the three dimensions of sustainability, and whether any kind of progress has been made in this regard. Accordingly, it set out to answer these research questions: What are the prevailing design strategies of the compact city model, and in what ways do they mutually complement, or beneficially affect, one another as to generating the expected benefits of sustainability? To what extent does the compact city model contribute to and balance the three goals of sustainability?

This study has shown that compactness, density, diversity, mixed land use, sustainable transportation, and green space are the prevalent design strategies of compact city planning and development, with the latter being contextually linked to the concept of green structure, an institutional setup under which the two Swedish cities operate. Moreover, the underlying strategies of the compact city are not mutually exclusive and thus must take place or exist at the same time in order to guarantee the viability and sustain the performance of the compact city regarding its contribution to the three goals of sustainability. It can be concluded that the compact city is a very complex urban planning and development approach that involves several dimensions that are supposed to work together synergistically.

In addition, this study has demonstrated that the compact city model as practiced by the two cities is justified by its ability to contribute to the environmental, economic, and social goals of sustainability. Hence, these cities are strategically planned to respond to the challenges of urban development in terms of urbanization and its dimensions (physical, environmental, economic, ad social) in line with the vision of sustainability. However, the economic goals of sustainability dominate over the environmental and social goals of sustainability, notwithstanding the claim about the three dimensions of sustainability being equally important at the discursive level. Nevertheless, new planning measures are being developed and implemented to strengthen the influence of the environmental and social goals over urban planning and development practices towards balancing the goals of sustainability. The main issues identified that the two cities are struggling with are green space loss, noise pollution, socio–economic segregation, and social inequity.

Providing generalizable conclusions in this study emanates from not only conducing two case studies in a country with a national focus on, and planning tradition for, sustainability on the longest established and most prevalent sustainable urban form, but also from reviewing many other theoretical and empirical studies on this phenomenon. In view of that, it is safe to argue that this study is of a macroscopic nature, and the outcome is analytically and practically generalizable. Indeed, compact cities are endorsed as a response to critical environmental, economic, and social challenges by turning cities more efficient, equitable, livable, vibrant, and attractive. To put it differently, agglomeration, proximity, and diversity have been demonstrated to promote environmental quality, social equity, accessibility, life quality, innovation, economic viability, and rural land and natural area protection. However, the compact city model involves conflicts when attempting to balance between the three goals of sustainability.

As regards the "so what" strategy, this study suggests that the compact city is not addressing and overcoming the challenges of sustainability based on the most effective approach when they focus exclusively technically on the design of the built form in planning in the face of the escalating scale and rate of urbanization and the wicked problems and intractable issues characterizing cities as complex systems. Indeed, this study illuminates, among others, how emerging planning practices incorporating the environmental and social dimensions of sustainability generate conflicts and contentions within the compact city model. These issues may stimulate new endeavors and opportunities towards finding more effective ways to further enhance and advance this widely advocated model, nevertheless. Regardless, the field of compact urbanism needs to extend its ambit beyond the built form of the city to include more innovative solutions and sophisticated approaches by unlocking and leveraging the potential of advanced ICT.

In that respect, more in–depth knowledge on planning practices is needed to capture the vision of sustainable urban development, so too is a deeper understanding of the multi–faceted processes of change to achieve sustainable urban forms. In this regard, the core questions that would potentially broaden our knowledge on how compact cities can harness their potential through the underlying design strategies and balance the three goals of sustainability in planning and development practices include:

- What is the most effective approach to introducing environmental, economic, and social concerns in the planning process, and what kind of measures are needed to integrate such concerns early on?
- To what extent can advanced technologies support joined-up planning, a form of integration and coordination which enables system-wide sustainability effects to be monitored, understood, analyzed, and built into the very designs and responses characterizing the operations and functions of the compact city?
- What kind of advanced technologies are available that can be implemented to make the planning process more dynamic based on constantly updated information on the operations and functions of the compact city?
- Currently urban dashboards are offering the opportunity for providing an integrated view and synoptic intelligence of the way the modern city is performing and functioning in real time. To what extent can this development aid expert and no-expert users in interpreting and analyzing the visualized information and allow citizens to monitor the city for themselves, all for the benefits of the compact city?
- To what extent can the aggregation of real-time data contribute to dealing with changes in the compact city at any spatial and time scale, especially the current datasets can show the city functioning in real-time and how longer term changes can be detected thanks to the IoT and its ubiquitous sensing network?
- To what extent can short–termism in urban planning, i.e., the process of measuring, evaluating, modelling, and simulating what takes place in the city over hours, days, or months, change the way the compact city functions as to focusing on much shorter term problems and issues than before with respect to the different aspects of sustainability?
- What is the potential of developing and applying urban intelligence functions in the form of innovation labs to capture how the compact city is changing in its nature on the basis of its real-time functioning, and to generate more effective urban structures, forms, and spatial organizations that improve sustainability, efficiency, resilience, equity, and the quality of life?
- To what extent can emerging technologies leverage the design strategies of the compact city in ways that enhance and optimize its processes and practices by continuously evaluating its contribution to the three goals of sustainability and their integration?

The present study offers insights that can inform future research agendas on sustainable urbanism, More specifically, it provides the grounding for further in–depth research on compact urbanism, not least in the developed countries that support sustainable development practices. We would particularly like to encourage qualitative research to further illuminate the strategies of the compact city model and the assumptions behind the associated initiatives in different contexts. And hence the claims that this model can make urban living more sustainable, irrespective of the context where it is embedded. This is justified by the increasing demand for practical ideas from the ecologically advanced nations about how to achieve the required level of sustainability through compact urbanism from policymakers and practitioners from other developed countries around the world. Further research should focus on providing the knowledge that these actors will need to make informed decisions about how to contribute and support the balancing of the goals of sustainability through compactness in their own national and local contexts. Moreover, as this study has demonstrated that compact urbanism practices, strategies, and goals already exist across the selected cities, it would be useful and interesting to carry out a wider and more varied comparison (involving cities from other Scandinavian and European countries) with a view to revealing more general trends in compact urbanism. Taking up this in future research is indeed justified by the limitation to the present study, which pertains to the case selection that included only Swedish cities. Due to this bias in the case selection, it is moreover conceivable that potentially more strategies of the compact city for particularly supporting the balancing of the three goals of sustainability exist in other cities in Europe. In addition, we would like to draw the attention of future researchers to the tension between the densification of the strategic urban areas targeted by development and the safeguarding of green areas located in such areas, as well as to the extent to which the new measures being developed and implemented to address socio–economic disparities are delivering the expected outcomes. Lastly, a sequel to this work and thus part of our future research is to integrate the compact city, the eco–city, and the data–driven smart city into a novel model of urbanism for the purpose of improving, advancing, and maintaining the contribution of sustainable cities to the goals of sustainability. This is one among many other opportunities that can be explored towards new approaches to smart sustainable urbanism.

Finally, the concepts, ideas, and findings presented in this study for policy makers provide practical clues as well as lessons on the expected benefits of compact urbanism as to its contribution to the three goals of sustainability, in particular the set of measures being implemented to support their balancing through institutional practices. Most of the time, when it comes to compact city development, contradictions, uncertainties, contentions, and even disputes emerge during the cooperation and interaction between policymakers, planners, developers, engineers, government officials, industry experts, and thought leaders as part of a comprehensive team, irrespective of whether the city is badging or regenerating itself as compact or sustainable. This phenomenon is nevertheless common in all urban development projects and initiatives due to the difficulty of aligning and accommodating the interests and expectations of the different stakeholders in the city. Regardless, learning from the experience and knowledge of the emerging or leading cities in their areas of expertise is a common way to formulate and implement urban policies and strategies through drawing positive and negative lessons. We expect this trend to continue in the future and hope to have contributed our share to improving that practice.

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Author contributions

S.E.B. conceived the study, conducted the literature review, collected and analyzed the data, and wrote the manuscript. J.K. and M.K. reviewed the manuscript. The authors read and approved the final version of this manuscript.

Declaration of competing interest

The authors declare no conflict of interest.

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Paper 7

Smart Eco–City Strategies and Solutions: The Cases of Royal Seaport, Stockholm, and Western Harbor, Malmö, Sweden

urban science

MDPI

Case Report

Smart Eco-City Strategies and Solutions for Sustainability: The Cases of Royal Seaport, Stockholm, and Western Harbor, Malmö, Sweden

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Abstract: Sustainable urbanism is seen today as one of the keys towards unlocking the quest for a sustainable society. As a central paradigm of sustainable urbanism, the eco-city is promoted by global and local policies as one of the preferred responses to the challenges of sustainable development. It is argued that eco-city strategies are expected to deliver positive outcomes in terms of providing healthy and livable human environments in conjunction with minimal demand on resources and thus minimal environmental impacts. As such, it is pertinent to examine how the eco-city model and especially its three sustainability dimensions is practiced and justified in urban planning and development at the local level. This is motivated by the increased interest in developing sustainable urban districts. In this light, this study seeks to answer the following two questions: What are the key strategies of the eco-city district model, and in what ways do they mutually complement one another in terms of producing the expected tripartite value of sustainability? To what extent does the eco-city district model support and contribute to the environmental, economic, and social goals of sustainability? To illuminate the phenomenon of the eco-city district accordingly, a descriptive case study is adopted as a qualitative research methodology, where the empirical basis is mainly formed by urban planning and development documents in two eco-city districts—Royal Seaport, Stockholm, and Western Harbor, Malmö, Sweden—in combination with qualitative interview data, secondary data, and scientific literature. This study shows that the eco-city district models of SRS and Western Harbor involve mainly design and technology, supported with behavioral change, as key strategies and solutions for achieving urban sustainability. Design encompasses greening, passive solar houses, sustainable transportation, mixed land use, and diversity. And technology comprises green technologies, energy efficiency technologies, and waste management systems. Design contributes to the three goals of sustainability, and technology contributes mostly to the environmental and economic goals of sustainability. Behavioral change is associated with sustainable travel, waste separation, and energy consumption. Moreover, at the core of the eco-city district model is the clear synergy between the underlying strategies in terms of their cooperation to produce combined effects greater than the sum of their separate effects with respect to the benefits of sustainability. Further, this study demonstrates that while the environmental, economic, and social goals of sustainability are represented in eco-city district strategies on a discursive level, institutionalized planning practices show that the environmental goals remain at the core of planning, while the economic and social goals still play second fiddle. Nevertheless, new measures have recently been implemented in Western Harbor that are expected to strengthen their influence over urban development practices, whereas the Royal Seaport program mainly focuses on the environmental and some economic aspects, which is a shortcoming that should be recognized and dealt with.

Keywords: eco-city; sustainable city; sustainable urbanism; planning practice; development strategy; sustainability goals; technology; design; smart solution; Sweden

1. Introduction

Since its widespread diffusion in the early 1990s, sustainable development has significantly influenced urban planning and development as manifested in the emergence and prevalence of sustainable urban forms across the globe, especially eco-cities. A number of recent international reports and policy papers argue that the eco-city model has positive effects on resource efficiency, climate change, citizen health, and economic growth, and there are numerous actors involved in the academic and practical aspects of the endeavor of ecological urbanism, undertaking research and developing and implementing policies to tackle the underlying challenges.

In the early 1990s, the discourse on sustainable development led to the emergence of the eco-city model, which has become one of the preferred responses to the challenges of sustainable development. Richard Register defined an eco-city in 1987 as 'an urban environmental system in which input (of resources) and output (of waste) are minimized' [1]. As the concept has become more established, the meanings associated with it and the diversity of initiatives and projects adopting the label have spread worldwide. However, as an umbrella concept, the eco-city encompasses a wide range of urban-ecological proposals that aim to achieve sustainability. These approaches emphasize renewable energy (e.g., solar, wind, geothermal, etc.), passive solar design, green structure, ecological and cultural diversity, and environmentally sound policies [2,3]. They propose a wide range of land use, environmental, economic, social, and institutional policies that are directed towards managing urban spaces to achieve sustainability. Remarkably, management is the core of many approaches to the eco-city. As such, this encompasses how the urban landscape is organized and steered rather than the physical shape of the city and thus its spatial arrangements. Hence, the city is managed to achieve sustainability through different policies related to its dimensions [4–7]. For example, the well-known Agenda 21 of United Nations Conference on Environment and Development proposes integrated management at the urban level to ensure that environmental, economic, and social factors are considered together in a framework for the sustainable city [6]. An eco-city secures ecologically sound, socially beneficial, and economically viable development that is supported by planning, design, and transportation [8,9].

However, in the current climate of unprecedented urbanization and increased uncertainty, it may be more challenging for cities in developed countries to configure themselves more sustainably/ecologically. The predicted 70% rate of urbanization by 2050 [10] reveals that urban sustainability/ecology is a key factor in global resilience and viability to forthcoming changes. This implies that the city governments will face significant challenges pertaining to environmental, economic, and social sustainability due to the issues engendered by urban growth. These include increased energy consumption, pollution, toxic waste disposal, resource depletion, inefficient management of urban infrastructures and facilities, inadequate planning processes and decision-making systems, poor housing and working conditions, saturated transport networks, endemic congestion, and social inequality and vulnerability [11,12]. In a nutshell, urban growth raises a variety of problems that tend to jeopardize the sustainability of cities, as it puts an enormous strain on urban systems and processes as well as on ecosystem services. Therefore, much emphasis has been placed on framing sustainability in cities around the world [13]. One aspect of such framing is the increasing interest in planning and developing environmentally sound and sustainable urban districts as a center for innovations and practical implementation, and as a way of incorporating sustainability in the built environment and hence redesigning and restructuring urban places.

A large body of work has investigated the presumed outcome of the eco-city achieved through planning practices and design strategies. More specifically, scholars have discussed to what extent it produces the expected environmental, economic, and social benefits of sustainability (e.g., [2,8,14–17])—with more of a focus on the natural environment and ecosystems than economic and social aspects [18]. This line of research thus directs attention to either the ecological dimension of sustainability or the tripartite composition of sustainable development. Moreover, a recent wave of research has started to focus on amalgamating ecological cities and sustainable cities with smart cities on the basis of advanced Information and Communication Technology (ICT), especially big data technology and its novel applications, to improve the contribution of sustainable urban forms to the goals of sustainable development (e.g., [2,3,11,14,19–26]). These research areas open the way for cross-domain analyses in terms of addressing and integrating the environmental, economic, and social facets of the eco-city. This study follows this path by examining how the eco-city district, and especially its three sustainability dimensions, is practiced and justified in urban planning and development. The two research questions driving this research are: what are the key strategies and solutions of the eco-city district model, and in what ways do they mutually complement one another in terms of producing the expected tripartite value of sustainability? To what extent does the eco-city district model support and contribute to the environmental, economic, and social goals of sustainability? To illuminate the phenomenon of the eco-city district accordingly, a descriptive case study is adopted as a qualitative research methodology, where the empirical basis is mainly formed by urban planning and development documents in two Swedish eco-city districts—Royal Seaport, Stockholm, and Western Harbor, Malmö—in combination with qualitative interview data, secondary data, and scientific literature.

This article unfolds as follows. Section 2 describes and discusses the eco-city in terms of definitions, models, ideals, and research gaps. Section 3 outlines, justifies, and elaborates the research methodology. Section 4 presents the results. Section 5 discusses the results. Finally, the article concludes, in Section 6, by summarizing the main findings, providing some reflections, and suggesting some avenues for future research.

2. Eco-City as an Approach to Sustainable Cities

2.1. Definitions

There are multiple views on what a sustainable city should be or look like and thus various ways of conceptualizing it. Generally, a sustainable city can be understood as a set of approaches into operationalizing sustainable development in or practically applying the knowledge about sustainability and related technologies to the planning and design of existing and new cities or districts. It represents an instance of sustainable urban development, a strategic approach to achieving the long-term goals of urban sustainability. Accordingly, it needs a balance between the environmental, economic, and social goals of sustainability as an integrated process. Such a balance can lead more opportunity to make the city greener, fairer, and more profitable for different stakeholders (Figure 1).

Figure 1. Triangular conflict among key contributors to achieve sustainability. Source: [27].

Sustainable cities have been the leading global paradigm of urbanism (e.g., [6,11,13,28]) for more than three decades. There are different approaches to sustainable cities, which are identified as models of sustainable urban forms, including eco-cities, compact cities, green cities, new urbanism, landscape urbanism, and urban containment. Of these, eco-cities are often advocated as a more environmentally sound and sustainable approach.

The idea of the eco-city is widely varied in conceptualization and operationalization. To put it differently, there are multiple definitions of the eco-city, depending on the context—urban initiatives and projects in terms of the planning and development practices pursued to achieve it. Generally, an eco-city is a human settlement which emphasizes the self-sustaining resilient structure and function of the natural environment and ecosystems. It seeks to provide a healthy and livable human environment without consuming more renewable resources than it replaces. Roseland [9] argues that there is no single accepted definition of the eco-city, rather a collection of ideas about concepts.

2.2. Eco-City Models

It is not an easy task to develop a clear, comprehensive vision of what an eco-city actually looks like. Indeed, there are different models of the eco-city focusing on planning and developing sustainable cities and communities based mainly on two key distinctive design principles and strategies, namely passive solar design and greening [6,14]. While these models share some features, in many cases, they focus on different aspects and comply with different criteria, including taking a holistic approach, interconnections of subsystems, adaptability, and planning and design procedures, with a substantial focus on the ecological aspects of sustainability. Examples of models that emphasize passive solar design include the ecovillage, solar village [29], Solar City [30], and cohousing [31]. Examples of models that combine passive solar design and greening include Eco-City ([9,32]), Ecological City [33], the Environmental City, Green City, Sustainable City ([34–36]), Sustainable Neighborhood [37], Sustainable Urban Living [38], Living Machines [39], and Garden City [40].

Other models, which are based on a particular set of green or smart technology solutions for achieving the goals of environmental sustainability, include SymbioCity [41], Carbon Neutral City, Zero Energy City, Zero Carbon City, eco-Municipality, eco-Industrial Park [30], Low Carbon City ([31,41]), Net Zero Carbon Community [42], Eco2 City [43], Smart Eco-City ([22,25]), and Ubiquitous Eco-City [26].

In light of the above, what exactly constitutes the eco-city as an overarching approach to sustainable urbanism seems to be even more unclear and thus difficult to pin down. Today an ever-increasing range of existing districts, cities, as well as new and planned urban initiatives and projects are labelled eco-cities [17]. Eco-districts focus on community collaboration, integrated communication, and management to help cities to be more successful by working together. Nevertheless, the way ecological urban initiatives and projects conceive of the eco-city status reflects more divergences than convergences [3,14]. In other words, the guiding planning documents in this regard tend to be largely developed as independent islands of locally ecological sustainability. Accordingly, it is more appropriate to think of the eco-city as an ambition that can be achieved through multiple ways.

2.3. Eco-City Ideals

The implicit image of an eco-city has proven to be a highly influential translation of what a sustainable city should be, carried by the significance of the design principles and strategies underlying this model of sustainable urban form [11,14,19]. Ideally, an eco-city secures ecologically sound, socially beneficial, and economically viable development that is supported by sustainable planning, design, and transportation through a set of policies covering the different aspects of urban sustainability. A well-designed eco-city should be able to achieve all of the benefits of sustainability. Accordingly, the eco-city becomes an all-encompassing concept for urban policy making processes and planning practices. Irrespective of the way the idea of the eco-city has been, and can be, conceptualized and operationalized, there are still some criteria that have been proposed to identify what an ideal 'eco-city' is or looks like, comprising the environmental, social, and economic goals of sustainable development. Irrespective of the way the idea of the eco-city has been, and can be, conceptualized and operationalized, there are still some criteria that have been proposed to identify what an ideal 'eco-city' is as aiming for the environmental, social, and economic goals of sustainability (Table 1):

Table 1. Criteria of an ideal eco-city. Sources: ([8,9]).

- Operates on a self-contained local economy that obtains resources locally
- Maximizes energy and water efficiency, thereby promoting conservation of resources
- Manages an ecologically beneficial waste management system that promotes recycling and reuse to create a zero-waste system
- Promotes the use and production of renewable energy, thereby being entirely carbon neutral
- Has a well-designed urban city layout that promotes walkability, biking, and the use of public transportation systems
- Ensures decent and affordable housing for all socio-economic and ethnic groups and improves jobs opportunities for disadvantaged groups
- Supports urban and local farming
- Supports future progress and expansion over time.

As added by Graedel (1999) [44], the eco-city is scalable and evolvable in design in response to urban growth and need changes. However, scholars have often critically discussed to what extent the eco-city produces the expected environmental, economic, and social benefits of sustainability. Ideally, for sustainability to be achieved, its environmental, economic, and social dimensions need to be in balance. Whether this is actually the case in the eco-city initiatives or projects varies from one to another (see [17] for further discussion).

2.4. Research Gaps and Issues

The issue of sustainable cities has been problematic, whether in theory or practice [12,14], and so is knowing to what extent we are making progress towards urban sustainability in the face of urbanization [11,13]. It is not an easy task to judge whether or not a certain model of sustainable cities is sustainable [45]. However, the ultimate goal of the endeavor is to develop a more theoretically and practically robust model of sustainable cities [2,3]. This has indeed been one of the most significant intellectual and practical challenges for more than three decades (e.g., [6,11–14,19,45]). As concluded by Jabareen (2006) [6], neither real-world cities nor scholars have yet developed convincing models of sustainable cities. In a nutshell, sustainable cities are associated with a number of problems, issues, and challenges, and hence much more needs to be done considering the very fragmented, conflicting picture that arises of change on the ground in the face of the expanding urbanization. Bibri and Krogstie [2] provide a detailed critical review of eco-cities as an approach to sustainable cities in terms of their deficiencies, limitations, difficulties, and uncertainties, as well as the opportunities being offered by advanced ICT to address them.

The eco-city has been criticized as an idea that is loosely defined from a set of ostentatiously attractive projects as expensive schemes with aesthetic and commercial ends intended to satisfy a local or regional ambition to invest in ecological sustainability without posing a more theoretically focused and globally applicable approach. In addition, Cugurullo (2016) [46] questions the sustainability of the so-called eco-city by investigating the extent to which it is developed in a controlled and systematic manner as its developers claim. More specifically, the author counterclaims mainstream understandings of ecological urbanism, arguing that what are promoted as cohesive settlements shaped by a homogeneous vision of the sustainable city are actually fragmented cities made of disconnected and often incongruous pieces of urban fabric. In reference to eco-cites, Holmstedt, Brandt and Robert (2017) [47] point out that implementing sustainable solutions is more difficult because no unified practical definition is still accepted even if the subject of sustainability has been hotly debated more than three decades, and most projects act dishonesty in order to gain an advantage by not defining what is meant by sustainability and not meeting all requirements. In addition, in urban planning and policy making, the concept of the eco-city 'has tended to focus mainly on infrastructures for urban metabolism—sewage, water, energy, and waste management within the city' [23] (p. 3), thereby falling short in considering smart solutions in relation to urban processes and practices (e.g., [11,12,14,24,48]).

3. Research Methodology

3.1. Case Study Inquiry

Case study research has long been of prominence in many disciplines. As a research methodology, case study research is well established in the social sciences and other scientific and technological fields. Creswell et al. (2007) [49] describe the case study methodology as a type of design in qualitative research, an object of study, and a product of the inquiry. The authors conclude with a definition that collates the hallmarks of key approaches and that represents the core features of a case study: 'a qualitative approach in which the investigator explores a bounded system (a case) or multiple bounded systems (cases) over time through detailed, in-depth data collection involving multiple sources of information ... and reports a case description and case-based themes' [49] (p. 245). The case study approach is usual when multiple sources of evidence are used [50,51], e.g., documents and reports, observations, interviews, and so on. The use of multiple methods to collect and analyze data is found to be mutually informative in case study research, together providing a more synergistic and comprehensive view of the issue being studied ([51–55]).

3.2. Descriptive Case Study Characteristics

Case study research can be used to study a range of topics [51,54,56,57]. With that in mind, this case study uses a descriptive design—an approach which is focused and detailed, and in which questions and propositions about the phenomenon of the eco-city are carefully scrutinized and articulated at the outset. The articulation of what is already known about this phenomenon is called a descriptive theory, which pertains to sustainable urban forms in this context. Therefore, the main goal of this descriptive case study is to assess the selected cases in detail and in depth based on that articulation of a descriptive theory. This research design intends to describe the phenomenon of the eco-city in its real-world context [21,51]. Worth noting is that there is not enough evidence to support this phenomenon or explain how or why it works.

Descriptive research here involves the description, analysis, and interpretation of the present nature, composition, and processes of two Swedish cities, where the focus is on the prevailing conditions, or how these cities behave or function in the present in terms of what has been realized and the implementation of plans based on the corresponding practices and strategies. This entails the ongoing and future activities to be undertaken in accordance with the time horizon set in the planning and development documents. Moreover, as an urban event based on two instances, the eco-city involves a set of indicators of an integrated city system in operation that requires an analysis to allow obtaining a broad and detailed knowledge about such system. To achieve this objective, this descriptive case study consists of the following steps:

- Using a narrative framework that focuses on the eco-city as a real-world problem and provides essential facts about it, including relevant background information.
- Introducing the reader to key concepts, strategies, and policies relevant to the problem under investigation.
- Explaining the actual solutions in terms of plans, the processes of implementing them, and the outcomes.
- Offering analysis and evaluation of the chosen solutions and related issues, including strengths, weaknesses, tradeoffs, and lessons learned.

Considering the above, one of the essential requisites for employing case studies stems from one's motivation to illuminate a complex phenomenon [51,53,54].

3.3. Selection Criteria, Unit of Analysis, and Data Collection and Analytical Methods

The rationale for selecting Swedish eco-city districts as cases for investigation is that Sweden is among the Scandinavian countries that have exemplary practical initiatives in sustainable cities, notably eco-cities. According to several rankings, Sweden, Norway, Finland, Germany, the Netherlands, and Japan have the highest level of sustainable development practices [58]. Several empirical studies identify, from the mid-1980s onward, increasing ecological disruption in most of the ecologically advanced nations, such as Sweden, Denmark, Germany, the Netherlands, and Japan [59].

In the context of this article, the two Swedish cities selected have been receptive to the eco-city ideal as well as engaged in ecological planning for almost two decades. They have chosen the eco-city strategy as the most effective planning system that can go hand in hand with sustainable development in light of the relevance and usefulness of the findings produced by many studies in the field of sustainable urbanism. As such, they are seen as successful examples of ecological urbanism, as well as critical cases in sustainable urban development. This is due to their long planning traditions and the existence of relatively solid economic resources at the local level, the national focus on sustainability in Sweden, and the wide authorization given to local authorities [60,61]. Moreover, they express environmental and sustainability ambitions in their master and comprehensive plans, support progress and expansion over time, and experience developmental pressure on their landscapes due to urbanization. Additionally, it was important to ensure that there was sufficient information available in the public realm to conduct an analysis on these two cases. On the basis of all these criteria, Royal Seaport in Stockholm and Western Harbor in Malmö have been selected as eco-city districts for investigation. They illustrate how ambitious districts handle the environmental and sustainability challenges, and how different values and interests are weighted and secured through urban planning and development.

The unit of analysis, the entity that frames what is being analyzed in this study, includes the strategies of the eco-city model and the extent to which they produce the environmental, economic, and social benefits of sustainability. This is essential to focalizing, framing, and managing data collection and analysis. To identify the perceived link between the eco-city dimensions and the environmental, economic, and social goals of sustainability, the common concepts related to the eco-city model (notably greening, passive solar design, energy, waste, and transportation) were searched for in the two cities' comprehensive plans. The broad concepts represented by these terms linked to the environmental, economic, and social sustainability goals were then mapped. This procedure enabled us to focus on strategies and goals directly linked to the eco-city city model.

In addition, the two districts' master plans, programs, policy documents, and project descriptions were identified and analyzed using a thematic analysis, which is a widely used analytical technique within qualitative research. Thematic analysis is particularly (albeit not exclusively) associated with the analysis of textual material. Generally, this approach emphasizes identifying, analyzing, interpreting, and reporting themes, i.e., important patterns of meaning within qualitative data that can be used to address the problem under investigation. Thematic analysis is generally flexible in terms of theoretical and research design given that it is not dependent on any particular theory or epistemology: multiple theories can be applied to this process across a variety of epistemologies.

Thematic analysis is an umbrella term for a variety of different approaches, which are divergent in regard to procedures. We adopted an inductive approach to thematic analysis, which involves allowing the data to determine the set of themes that is to be identified. That is to say, we developed our own framework based on what we find as themes (inductive) by discovering patterns, themes, and concepts in the data.

The main steps of the analytical process are as follows:

1. Review of city data (i.e., master plans, programs, policy documents, and project descriptions, etc.) and the scientific literature that is related to the eco-city model. The outcomes of this process are numerous themes that are associated with this model. It is important to obtain a comprehensive

understanding of the content of the documents and scientific literature and to be familiarized with all aspects of the data. This step provides the foundation for the subsequent analysis.

2. Pattern recognition (searching for themes) entails the ability to see patterns in seemingly random information. The aim is to note major patterns within the result of the first step. This second step looks for similarities within the sample and codes the results by concepts and themes. Coding involves identifying passages of text that are linked by a common theme, indexing the text into categories and therefore establishing a framework of thematic ideas about it. In this step, the preliminary codes identified are the features of the data that appear interesting and meaningful, and the relevant data extracts are sorted according to overarching themes. It is important to allude to the relationship between codes and themes.
3. Reviewing and naming themes are about combining, separating, refining, or discarding initial themes, as well as naming them, in accordance with the three dimensions of sustainability as related to the eco-city model. Data within themes should cohere together meaningfully and be clear and identifiable in terms of the distinction between them. A thematic 'map' is generated from this step. Subsequently, theme names are provided with clear working definitions capturing the essence of each theme.
4. Producing the report involves transforming the analysis into an interpretable piece of writing by using vivid and compelling data extracts that relate to the themes, research question, and literature. The report must go beyond a mere description of the themes and portray an analysis supported with empirical evidence that addresses the research questions.

Furthermore, the results of the document analysis were triangulated with local thematic plans relevant to the three dimensions of sustainability, and to information from the two cities' websites, newspaper articles/internet discussions, observations, and interviewees.

Primary data were collected through face-to-face and telephone interviews with a total of 10 interviewees, including planners, architects, developers, and administrative servants. They were selected from the ongoing projects of SRS and Western Harbor, especially those working within the areas that involve contentious and challenging issues based on both the outcome of the previous empirical studies carried out in relevance to this study as well as the arguments advanced by the critics of the eco-city model. One of the key objectives of the interviews was to corroborate the progress made by the two municipalities as to the development and implementation of new measures to address the issues related to the economic and social dimensions of sustainability. As regards the environmental dimension of sustainability, the objective of the interviews was to document the practical advances claimed to be made in the field of sustainable urban development, as well as the extent to which the eco-city district strategies have been implemented according to the plan.

The interviews were mostly unstructured and guided by the three sustainability dimensions in terms of the past and current issues related to the above mentioned topics. They were meant to be used in ways that can be adapted to the interviewees' roles and interests. This means that the interviewees were asked different questions. Findings were reported as statements relating to the three dimensions of sustainability in terms of strategies and solutions, and included complementing, substantiating, and conflicting statements.

In addition, a set of face-to-face and telephone conversations was conducted with some researchers and scholars at Lund University, Malmö University, and Royal Institute of Technology. This was particularly important in providing insights into some ongoing projects and useful knowledge regarding environmental sustainability in the context of sustainable cities. As far as the face-to-face conversations are concerned, they took place with no schedule set in advance, whenever the circumstances allowed.

3.4. On the Case Study Cities and Districts

Centrally located in the growing Baltic region, Stockholm is the largest city in Sweden, the capital of Sweden, and the most populous urban area in Scandinavia. Approximately 1.6 million people live in the urban area, 2.4 million in the metropolitan area, and 965,232 in the municipality. Moreover, Stockholm is an important global city and one of the world's cleanest capitals and metropolises due to the absence of heavy industry and fossil fuel power plants. Indeed, it has a long history of environmental work and was the first city to be granted the European Union's Green Capital award by the European Commission in 2010 [62] because of its high environmental standards and ambitious goals for further environmental improvement. This involves climate change, public green areas, air quality, waste and water management, wastewater treatment, sustainable land use, environmental management, and sustainable transport. In particular, the city has a long-term commitment to sustainable development and environmental enhancement.

The City of Stockholm is at the forefront of ecological thinking. It has very strong environmental policies and is focused on improving the quality of life of its citizens [63]. It argues that climate-adapted solutions will minimize energy use, waste, and transport requirements [64,65]. Hammarby Sjöstad will serve as a starting point in the quest for sustainable solutions for energy usage, waste handling, and transportation [65]. Accordingly, drawing on the lessons learned and the experiences gained from Hammarby Sjöstad, SRS as a world-class environmental city district has set three ambitious environmental goals, namely [66]:

1. To reduce CO_2 emissions from 4.5 tonnes in 2008 to a level below 1.5 tonnes per inhabitant by 2020.
2. To be fossil fuel free and climate + by 2030.
3. To be adapted to a changed climate, i.e., increasing precipitation.

In recent years, much of the environmental work within Stockholm has focused on developing new sustainable urban districts. One recent initiative, in addition to Hammarby Sjöstad, is the Stockholm Royal Seaport (SRS) district, with a vision to transform this district into a world class environmental city district. SRS is an area of 236 hectares that is being transformed from a brownfield zone into a site of 12,000 homes, 35,000 workplaces, 600,000 m^2 of commercial spaces, and parks and green spaces, with approximately 35,000 people to live and/or work in the area.

SRS is designated as an environmental profile area with the mandate to become a model of sustainable urban development [66]. It is among the key climate-positive projects in the world that are considered as examples of successful environmental and economic urban developments, demonstrating that cities can reduce carbon emissions and grow in climate friendly ways. While the vision of SRS is to become a world-class environmental city, its goals are ecological, economic, and social sustainability. Its vision relates to the goal established by the City of Stockholm to be fossil fuel free by 2050 [67]. In this respect, the SRS environmental profile should consolidate Stockholm's position as a leading capital in climate work, support the marketing of Swedish environmental technology, and contribute to the development of new technology [65]. The program for SRS aims to lead the way for SRS to become an environmentally and sustainably sound urban district, managing all three pillars of sustainability.

Malmö is the largest city of the Swedish County of Skåne and the third-largest city in Sweden, after Stockholm and Gothenburg, with a population of 316,588 inhabitants out of a municipal total of 338,230 in 2018 [68]. Being perfectly situated along the straights, it separates Sweden from Denmark, and also connects Sweden to Denmark through the Öresund bridge, whose opening in 2000 made Malmö Sweden's principal point of entry. Since the construction of the Öresund Bridge, Malmö has undergone a major transformation which can be seen more clearly in Western Harbor (Västra Hamnen) than in any other part of Malmö. The Municipality of Malmö had initially invested in residential development on the site by means of a European housing exhibition focused on sustainability—Bo01, exploring a drastic vision of future living intended to provoke discussion and to be a best practice exemplar pilot project for a mixed district. This event was held in Malmö in 2001.

Bo01 represents the first step in the process of transforming the 160 hectares of Western Harbor area into a sustainable urban district. When completed, the Western Harbor area will consist of a total of approximately 11,000 homes and 17,000 jobs, and over 20,000 people will be able to live in the area [69]. At the beginning of 2014, this district had approximately 4000 homes and approximately 10,000 jobs, in addition to a number of facilities and services [69]. The original plan created to redevelop this formerly industrial, waterfront real estate has led to the transformation of 18 hectares into a mixed-use residential community built according to sustainable principles.

Similarly, Western Harbor is designated as an environmental profile area with the mandate to become a model of modern eco-city district. Its aim is to become an international leading example of an environmentally sound, densely populated district, i.e., with an environmentally sustainable development profile that runs on renewable resources. The development of Bo01 in 2001 was to accommodate commercial and social uses, and related housing exhibition in 2002 showcased what was achievable in terms of planning, designing, and building to the highest energy efficiency and renewable energy standards. This in turn enabled the testing of new sustainable technologies and approaches to their application on a wider scale. However, the key goal of Western Harbor is to become an environmentally sound and sustainable urban district, integrating all three dimensions of sustainability, ecological, economic, and social [69].

4. Results: The Core Eco-City Strategies and Solutions for Achieving Urban Sustainability

In order to identify the key dimensions of the two eco-city districts and their link to the environmental, economic, and social goals of sustainability, as well as the extent to which they produce the expected benefits of sustainability in terms of its tripartite composition, we will now take a closer look at the two districts' planning and development documents. We begin with the environment dimension of the eco-city district as an approach to sustainable urbanism.

4.1. Environmental Sustainability

4.1.1. Sustainable Systems

The environmental targets set by SRS and Western Harbor are being supported by the application of cutting-edge environnmental technologies, including sustainable energy system, smart grids, smart communications, eco-cycle waste management, biogas and electric cars, sustainable buildings, sustainable transportation, as well as sustainable lifestyles.

Sustainable Energy System

The energy system is at the core of the planning practices and development strategies for both districts. One of the key strategies for sustainable urban development underlying the sustainability program for SRS is 'resource efficiency and climate responsibility.' In this respect, the City of Stockholm [66] argues that for the built environment to be robust over time, it is required that natural resources must be used efficiently, and that buildings and facilities are designed with high quality. Renewable energy generation and use is strongly advocated to make SRS fossil fuel free, and the future energy system in SRS is intended to be based on renewable sources. In the environmental and sustainability program for SRS, it is recognized that for the district to fulfill the ambition of becoming environmentally sustainable, the energy system plays an important part [70]. The Municipality of Stockholm set these energy requirements on urban developers: 55 kWh per m^2 x year and 30% locally produced electricity by renewables (Figure 2).

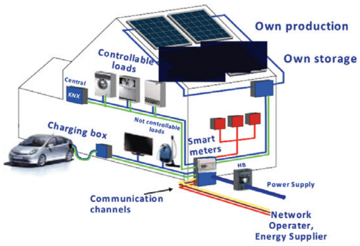


Figure 2. Local production of electricity.

Both requirements are associated with the energy goals set by SRS as shown in Table 2.

Table 2. Energy goals of SRS.

1.	Fossil fuel free by 2030.
2.	Large-scale net-zero houses and locally produced solar energy—electricity by renewables (Figure 2).
3.	Passive houses towards plus houses.
4.	Minimization of comfort cooling/use of passive cooling technology.
5.	Energy quality hierarchy (using high energy quality only when needed).
6.	Low level of energy use concerning products and systems.
7.	Bio-fueled combined heat and power (CHP) system, including recovery of waste/heat.
8.	Measuring energy usage in all households/buildings.
9.	Smart grids for electricity (and heat).

Stockholm has a strong tradition of using district heating as a well-developed, efficient system for the distribution of heating, cooling, and hot water to buildings (Werner 1989). Environmentally, Stockholm focuses on low-carbon development, most notably through widespread district heating and cooling systems (OECD 2013) [71]. The environmental and sustainability program for SRS states that the energy system in SRS must primarily be based on the bio-fueled CHP system [70], which entails local production of electricity by renewables and smart waste collecting system. Incineration of household waste is one of the main energy sources for district heating [71]. The energy requirements for the buildings in SRS are set high and will thus decrease the demand for heating in the area [70]. In this case, it is of importance to develop a flexible system in such a way that it can be adapted for use with other sources of energy as well as integrated with multiple systems. Hence, the utility provider Fortum is currently in the process of building a new bio-fueled CHP plant at its facility in Värtan, which is located in the SRS district [72]. The plant, as one of a number of ways that will make the vision of a sustainable and climate-smart urban environment become reality, will contribute to a further reduction in Stockholm's CO_2 emissions by generating 10% of its electricity needs and 25% of its district heating needs [65]. As it will distribute district heating to southern and central parts of Stockholm, in addition to SRS, it will contribute to reaching the ambitious emission reduction targets set by the City of Stockholm.

As acknowledged in the environmental and sustainability program for SRS, every part of the district that is affected by the energy system, e.g., buildings and infrastructure, must be highly effective, and the goal is that SRS will become a climate-positive district [70]. The results achieved in 2017 show, according to the sustainability report for SRS [66,73], that the energy consumption was reduced by 40% in total—energy performance lower than national legislation, and actual PVs production is 1 GWh/year. Requirements on energy, waste, and transportation as one of the smart sustainable solutions implemented by SRS are reducing GHG emissions by approximately 60% [74]. However, developing an energy system that is not dependent on fossil fuels involves delicate challenges and developing such a system for SRS as a single district can pose even greater ones.

The energy vision for the City of Malmö is that renewable energy sources will be phased in and fossil fuels phased out. Malmö's Energy Strategy has the goal of supporting the entire geographical area of the city with renewable energy by 2030 [75]. Energy efficient housing and sustainable buildings combined create ecological values, and investment in this area of urban ecology contributes to decreased energy resource use. Western Harbor is the 'the first climate-friendly district in Sweden' [69], and a great deal of attention in this district has been given to the use of natural resources, as well as recycled water, waste, and raw materials. Local energy production is integrated from the start throughout Western Harbor. The Bo01 area was planned to have, and is currently being served by, a 100% locally produced energy supply from renewable sources (Figure 3). This concept is based on local conditions for energy production and this equation is based on an annual cycle. In the Bo01 area, 1000 homes are supplied with energy from renewable sources: solar energy, wind power, and water through a heat pump that extracts heat from seawater and an aquifer (Malmö City 2006). Producing renewable energy, heat, and gas through wind, biomass, and sun is seen as Malmö's advantageous potential that should be used in the best manner. Renewable sources in Western Harbor, Bo01 (Malmö City [69,76] are presented in Table 3.

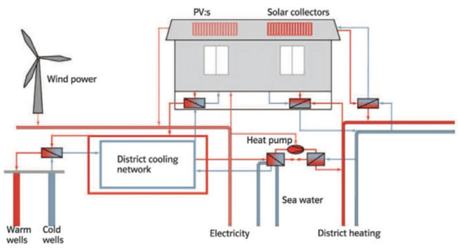


Figure 3. The Bo01 system: 100% locally renewable energy.

Table 3. Renewable sources in Western Harbor.

- In total, 1400 m^2 of solar collectors installed on the top of ten buildings with a calculated annual heat production amounting to 500 MWh. They complement the energy produced by the heat pump to supply the area.
- A large wind power station using a 2 MW wind turbine and 120 m^2 photovoltaic solar panels on the buildings to produce electricity for the apartments and homes, the heat pump, fans, and other pumps within the area. The wind turbine is 120 m in height when measured to the tip of the wings, with a calculated annual electricity production of 6300 MWh.
- The plants are linked to the energy systems in the city for district heating, district cooling, and the electricity grid. The solar collectors are directly connected to the district heating system, precluding the need for extra storage tanks.
- Low energy use in the buildings is a requirement, and each unit is only allowed to use 105 kWh/m^2/year, including household electricity.

Many buildings in Western Harbor have solar panels for both heat and power production. As stated in the current urban development of Western Harbor [69] (p. 14), 'There are a total of over 3000 m^2 of solar panels supplying heat to the district heating network. Some buildings also have small wind turbines on the roof . . . Nearly all dwellings in the Western Harbor district are heated by district heating, produced both from waste incineration and from solar energy and inter-seasonal storage in the bedrock.' The latter relates to the heat pump, which mainly extracts heat and cold from a natural underground reservoir and, to a lesser extent, cold from seawater. In the Western Harbor, there are 10 cold and warm wells in an aquifer at a depth of 40 to 70 meters placed in the ground. The water of the aquifer contains a stable temperature of 10–11 °C throughout the year and is used in the summer for storing heat and in the winter for storing cold.

In terms of passive solar design, Fullriggaren neighborhood, which was built in 2009–2013, constitutes the greatest collection of passive and low-energy buildings in Sweden, where renewable energy is produced locally via solar panels and cells [69]. It is the third development project for housing in Western Harbor and contains as many as 200 of the 600 dwellings that are passive houses. The preliminary evaluation of this neighborhood shows that the actual energy use is closer to the target than in the first phase, Bo01, where the energy use was higher than expected [69]. As one planner confirms, 'While several of the buildings have met the targets in the Bo01 area, there was a number of them where the energy consumption exceeds the target excessively, which had led to the investigation of the issue and the continuous measurement of the energy consumption in order to improve the situation in future urban development projects.'

Environmentally Smart Sustainable Solutions

In ranking 28 European capital cities based on how smart and sustainable they are using hierarchical clustering and principal component analysis (PCA), Akande, Gomes and Cabral (2018) [77] found that Stockholm is the leading Nordic capital city in this regard. The City of Stockholm (2017) [61] sets the following targets:

To use digitalization and new technologies to make it easier for residents and businesses to be environmentally friendly;
To reduce energy consumption and carbon footprint;
To provide sustainable solutions for modern transport;
To use digitalization and new technologies to stimulate biological diversity and conservation;
To produce goods and services in a resource efficient way with minimal environmental impact.

According to the City of Stockholm, an IoT-based infrastructure is highly important and the backbone for building smart sustainable cities. As Johansson Claes (2018) [78], a project leader, states, 'the reason we are establishing this is because we have a lot of challenges. We know that using the smart technologies can help us to be a better city, for the people that live there, work there and even the people that are visiting us.' It was also stated that the environmental department in the city is active with smart technologies. The smart eco-city district of SRS starts with a common vision in smart planning and design on the basis of IoT technology [74]. It was during the period 2015–2016 that an 'ICT network' was established in the City of Stockholm to find a more comprehensive way of using ICT, and that the name of the IT department of the City was changed to 'digital development' with a much broader take on ICT (Kramers, Wangel and Höjer 2016) [48]. The telecom company Ericsson, which is based in Stockholm, was the first company to give a presentation on smart sustainable cities, which had a major effect on people in the city in terms of how the digital and physical landscapes of the city can be merged together [48].

The City of Stockholm's main domains include smart traffic, smart lighting, air pollution, and sustainability (environmental and green policies). Some smart solutions include [66]:

- BigBelly: Waste bins using solar power and packing trash automatically when needed, with notification of when they need emptying.
- Smart lighting: Sensor-controlled LED lighting for pedestrian and bicycle paths, self-controlled-LED street lights with preset lighting schedules, and remote-controlled lights.
- Green IT for reducing environmental impacts: Energy-efficient buildings (monitoring and optimization), transportation (intelligent transport solutions), and digital meetings and mobile workings.

Small-scale tests were performed within the different areas of the city to determine whether smart technologies have been converted into pilot projects within the above mentioned domains [78]. Here, the IoT infrastructure is being used to establish and share data from different projects related to traffic, lighting, air pollution, and the environment, and the role of private companies should lie in establishing new services out of these data.

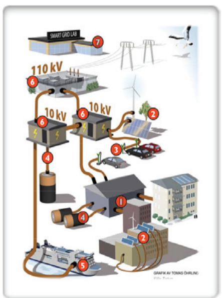
However, the strategic implementation of ICT was brought in by the environmental program for the City, which involved requirements that SRS should be smart in this direction. Therefore, the environmental targets set by SRS are being supported by the implementation of smart technologies. Among the smart sustainable solutions implemented by SRS are the establishment of digitalized monitoring and feedback processes, and triple and quadruple helix research and development (R&D) projects (e.g., the IoT, visualization, and circular economy [74]. The use of ICT within SRS pertains mainly to its role in reaching environmental targets as part of the digital city plan for the district.

The interview showed that the database systems for collecting the environmental data were secured and being used in SRS to give feedback and inform inhabitants. The City administration established a platform that can collect the environmental data given the importance of orchestrating the plethora of different systems. In SRS, ICT solutions are used to visualize and communicate energy use pertaining to households/buildings and smart sustainable system solutions. In this context, a new framework for Smart Urban Metabolism (SUM) has been implemented in SRS as part of a R&D project [79]. In this framework, four key performance indicators (KPIs) are generated in real time based on the integration of heterogeneous, real-time data sources, namely

(1) kilowatt-hours per square meter,
(2) carbon dioxide equivalents per capita,
(3) kilowatt-hours of primary energy per capita, and
(4) share of renewables percentage.

These KPIs are fed back on three levels (household, building, and district) on four interfaces, developed for different audiences. The long-term opportunities of SUM include enabling a new understanding of the causalities that govern urbanism and allowing citizens and city officials to receive feedback on the system consequences of their choices. The SUM model works at high temporal (up to real time) and spatial (down to household/individual) resolutions. In other words, it can, through integrating ICT and smart urban technologies, provide real-time feedback on energy and material flows, from the level of the household to the urban district as applied to SRS [79]. However, the most challenging barrier identified in relation to SUM is accessing and integrating siloed data from the different data owners, which is hard to overcome unless a significant value is perceived. Further, applying this framework at the city level has been limited by the lack of data at this scale [80]. This is one of the common challenges pertaining to the implementation of big data analytics and its novel applications in the context of smart sustainable cities [11,81].

Moreover, SRS has implemented a large-scale smart grid system, as illustrated in Figure 4.



1. Smart homes/buildings and demand response
2. Distributed energy systems
3. Integration and use of electric vehicles
4. Energy storage for customers and the grid
5. Smart electrified harbor
6. Smart primary substations
7. Smart grid lab (part of an innovation lab)

Figure 4. A large-scale smart grid in SRS.

In relation to environmental urban planning, Kramers et al. (2016) [48] address the uses of ICT in governance by improving the understanding on how the City of Stockholm administrations have worked with integrating ICT solutions for sustainability into the planning phase of SRS as a new urban development project. In this work, they track how ICT has become part of the environmental program for SRS and how it is conceived as regards the planning and implementation of green and sustainable technologies together with the expected outcomes. In addition, the authors identify a number of challenges for the development of SRS as a smart sustainable city district, which are summarized in Table 4.

Table 4. Challenges for the development of SRS.

- Lack of vision as regards the digital city plan.
- Lack of experience with and competence in working with ICT issues in urban planning.
- Understanding the interaction between individuals and environment (i.e., buildings, public spaces, transport solutions, etc.).
- Stakeholder involvement and management in the innovation process.
- Long time horizon in terms of negotiating agreements for planned areas.
- Short time horizon in terms of investments due to the limited scope and time of economic analyses.

The main conclusion of the authors revolves around how ICT and sustainability as practical approaches can be merged in the planning phase of new urban development projects.

As regards Western Harbor, all homes use Internet connections to enable quick access to energy consumption data. In several properties in the Bo01 area, there are ICT solutions for reading meters and control of energy use and ventilation [76]. In addition, the property Klyvaren 1, one of the four quarters of Kappseglaren, is one of the first completely carbon-neutral blocks of flats built, and next to Klippern 2, there is a pilot project for smart energy systems [69]. Unlike the Western Harbor district, ICT solutions have, to a certain extent, become integrated in the ambitions of developing the SRS district. In fact, the sustainable systems implemented in the Bo01 area create challenges in relation to their operation and management. One architect from the Municipality of Malmö said that: 'monitoring the performance and evaluating the success of the sustainable systems continues to be challenging due to their complexity as well as cost.' It is necessary to incorporate the energy system, the waste management system, buildings and facilities, and the transport system as socio-technical systems together with ICT solutions [48] through a distributed infrastructure of computing components, resources, and interfaces that facilitate the management of urban infrastructures and services [20,21,82,83].

However, as with all emerging ICT-enabled solutions, there are several challenges that need to be addressed and overcome in terms of urban planning, design, and development. These challenges in the context of SRS involve the following:

- Sustainable long-term management of the district,
- Long-term monitoring of its metabolism,
- Silo thinking within the district administrations, and
- The transition from pilot to large-scale implementation.

Regardless, long-term commitment of the Municipality of Stockholm is uncertain when political constellations change (red-green coalition versus blue coalition), despite the promising outcome of the inclusion of ICT in the central governance of the City of Stockholm. Kramers, Wangel and Höjer (2016) [48] distill some general lessons learned as to what worked well and what did not in terms of using ICT in the planning phase of SRS as part of city governance.

Sustainable Waste Management

It is important for SRS and Western Harbor as sustainable districts to have a waste management system which enables handling waste in an accessible, safe, and environmentally sustainable manner. A key strategy in this regard is to standardize the planning of waste sorting facilities in conjunction with housing and commercial properties. Larger waste sorting stations should be evenly distributed throughout the two districts and be connected to the city's waste infrastructure.

Waste management is an important strategy of the environmental and sustainability program for SRS. The vision is that the district should adhere to a waste hierarchy that reduces the amount of waste produced and prioritizes material-efficient products [70]. These must be re-used and recycled in terms of material and energy. The waste sorting system should be designed in a way that is accessible and understandable, and that makes it easy for residents in the SRS district to sort their waste in the correct and safe manner. Especially, a high degree of waste separation is part of the SRS goals, which implies that, for example, the household waste fraction should contain food residues and plastics [70]. The results achieved in 2017 show, according to the sustainability report for SRS [66,73], that 100% of the properties are connected to a vacuum waste collection system (Figure 5) and 100% of the kitchens have a waste disposal unit. SRS has high environmental sustainability ambitions, supported by the implementation of advanced technical solutions that can help to fulfill the vision. This must, however, be reinforced by great potential for behavioral change of the local residents through their engagement as part of environmental stewardship. Indeed, the residents are the actual forefront users of new technologies. One planner confirms that: 'It is up to the residents to use the waste collecting system in the correct way, as well as to adopt sustainable habits and lifestyles. Especially, the residents have no regulations to adhere to in this regard. Therefore, it is up to their goodwill and interests and the extent to which they want to live up to the vision of their district.'

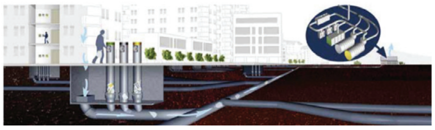


Figure 5. Smart waste collecting system.

It is also important to acknowledge wastewater and sewage fractions as important resources and, thus, to handle their integration in the sustainable energy system. This relates to the use of energy more efficiently through closed eco-cycles: solutions that do not strain the earth's resources. The SRS environmental and sustainability program states that the separation of sewage fractions must be feasible for generating biogas fuels [70]. However, concerns about the integration in question at wastewater treatment plants, coupled with the lack of ground space within the SRS area, has led to abandoning the system solutions that were proposed in the original plan for SRS and alternatively integrating them into existing wastewater systems at treatment plants in Stockholm [47]. The City of Stockholm (2010) [70] initially planned to have separate pipes for organic waste, e.g., separation of organic material from waste disposal systems and urine separation. The translation of the vision of SRS into reality has posed several challenges.

The Western Harbor district focuses on recycling, reuse, and minimization of consumption in all its cycles. In the Bo01 area, most dwellings have access to vacuum systems that are able to transport waste underground so that refuse trucks can stop outside, instead of driving into, the residential quarter to collect the waste [69]. This application involves the 147 in the Turning Torso, which have waste disposal units in their sinks that are connected to a separate collection tank from which refuse trucks can collect food waste. This new application proved to be so successful that it subsequently became standard in Fullriggaren quarter, where all 600 dwellings were fitted with waste disposal units from the start [69]. The waste management system in the Bo01 area 'was developed with the aim to create a system that minimizes the amount of waste, makes reuse and recycling possible and enables the use of waste and sewage as an energy source. Having waste separation units close to home is an important part of the planning of the area' [76] (p. 4). As part of the requirements for handling waste, it is made easy for the inhabitants in the Bo01 area to sort paper and packaging materials, as they do have a separation room in their house or close by.

All properties in Western Harbor should have access to facilities for separating packaging, food waste, and mixed waste. The City of Malmö has tried out various methods for collecting food waste in the district. The area of Fullriggaren is the greatest in Sweden in which organic waste is collected via waste disposal units, separate pipe networks, and collection tanks for biogas production [69]. In the Bo01 area, two parallel systems for handling food waste are tested: a centralized vacuum waste chutes system and food waste disposers in the sink [76]. With respect to the latter, the organic waste is ground and disposed in separate pipes to a collector tank underground, and the resulting sludge is taken to a biogas plant together with other organic waste and then transformed to biogas through the process of anaerobic digestion that can be used to fuel city buses and to produce heat and electricity [76]. The food waste collected throughout Malmö is also converted into bio-fertilizer that can replace artificial fertilizer on fields [69]. As regards the non-organic waste, it is deposited in one of three vacuum tubes located in the residential courtyards (Figure 5). Unlike SRS, Western Harbor has been successful in fulfilling the environmental goal pertaining to sustainable waste management, especially in relation to the energy system.

Sustainable Construction Materials

Waste is to a large extent a building issue when developing the districts of Western Harbor and SRS. Many of the materials used in modern buildings have negative environmental impacts or are associated with environmental problems, especially in the extraction and production phase [84]. A key strategy adopted by the City of Malmö is that the construction of building should be characterized by longevity and environmentally adapted materials [75]. Recycled material has been used in the underlying layers of the streets and alleys in Western Harbor, Bo01, and material in the streets and public spaces are based on the potential of future reuse and long life span [76].

Likewise, the environmental and sustainability program for SRS states that the building materials used to construct the district should be of high environmental performance, reusable, and selected using a life cycle perspective, and that the building waste should be kept to a minimum, sorted, and recycled [70]. One architect from SRS development group confirms that high requirements have been set on urban developers regarding construction materials in order to seek to acquire and develop areas in the district, which means that the operational goals of the environmental program for SRS are of high level in terms of implementation as well as maintenance. Among the smart and sustainable solutions implemented by SRS are sound and socially sustainable built-in materials and testing of innovation procurement and competition (e.g., construction consolidation center, pop-up reuse center) [74]. The ambitions for developing high-performing buildings and minimizing waste amounts as an alternative approach to construction materials in SRS gives the City of Stockholm a unique opportunity and position in this regard. Even with higher demands on the developers, construction companies have shown receptiveness and readiness to be part of the development of SRS, willing to consider new suggestions and agreeing to meet the higher requirements in set in the program for SRS, as the interview revealed. All property developers use the BASTA environmental assessment systems to comply with the requirements for construction materials [73].

4.1.2. Sustainable Transportation

Sustainable transportation is a key strategy for achieving environmentally sound and sustainable urban forms by means of providing services that produce environmental and social benefits and create a balance between what people need as to mobility and accessibility, in addition to environmental quality and neighborhood livability.

As a key component of sustainable transportation, the public transport system involves both the physical infrastructure, including roads, railroad tracks, sidewalks, and pedestrian paths, as well as the level and quality of services provided to citizens, e.g., great bus and train frequency and faster journey time. The public transport system in Stockholm and Malmö is seen as one of the most important driving factors for achieving the vision of SRS and Western Harbor respectively. Indeed, to achieve an environmentally sound and sustainable city district requires enhancing mobility and accessibility through transport infrastructure improvements. The transport system is planned to be improved by the creation of new links, enhancing existing networks, and influencing habits and movements.

In SRS, several public transportation connections such as subways, busses, trams, and ferry lines were planned and are being realized, and huge investments will be made in efficient public transport within and to SRS [65]. A metro station, Ropsten, is already in service along with several existing routes of public buses in SRS. Alongside the public transport system, important footpaths/walking tracks and bike paths/cycling lanes linking SRS to the businesses and shopping centers will be laid [65]. The SRS district is walkable and bicycle friendly and is approximately 8 to 10 minutes cycling distance to the city's Central Station. Similarly, there are plans for new cycle bridges linking Western Harbor to the inner city, and the MalmöExpressen represents a massive improvement in capacity and comfort for travel by bus to and from Western Harbor, in addition to other preparations being made for future tram links [69]. In addition, Malmö City (2015) [69] argues that as sustainable travel entails measures related to physical planning and influencing behavior, work is required on several different levels, involving both developing good physical conditions for people to choose to walk, cycle or take public transport as well as influencing behavior.

SRS is committed to, throughout its northern, middle, and southern parts, prioritizing walking, cycling, and public transport by ensuring an integrated network of pedestrian paths, cycling lanes, and parking facilities, as well as by expanding several routes of public buses and tram lines. A key strategy for sustainable urban development driving the sustainability program for SRS is 'accessibility and proximity.' In this respect, Stockholm City (2019) [66] argues that a prerequisite for transport planning in SRS is the implementation of a transport hierarchy, where walking and cycling become more convenient because of proximity to services in the local area, coupled with a clear connection between the area and a coherent urban fabric. Walking and cycling are associated with the close proximity to shops, amenities, and facilities in dense and diverse urban areas. However, the traffic hierarchy implemented by SRS is as follows [70]:

- Walking and cycling,
- Public transport (metro, buses, tram, boats),
- Car pools (biogas and electric), and
- Private cars (biogas and electric).

This traffic hierarchy and other communication patterns are meant to provide an opportunity for residents in SRS to move towards a sustainable transport system. As one transport planner confirms: 'The inhabitants in SRS have expressed commitment and appreciation for walking, cycling, and public transport, especially they are satisfied with the new improvements of transport infrastructure, and also SRS is located in close proximity to the city center.' Plans for new links and connections, good access to public transport, good availability of bicycle parking, enhanced pedestrian paths, and relevant restricted car parking that give priority to waling and cycling are the incentives that are planned to be introduced in pmissingractice as the district evolves in terms of its construction. While these incentives are crucial to moving towards a more sustainable transport system within the SRS district, the final outcome is yet to be seen, i.e., whether some parts of the plan will be abandoned or compromised.

In SRS, for example, the extension of the tramline was originally planned to be operational within the area upon the completion of the first construction phase, but this never happened during 2012 when the first residents moved into the area to the 670 new dwellings that were completed. The extension of the tramline into SRS has been delayed until 2020 [85]. However, it is important that the public modes of transportation are present within the district from an early stage in order to shift travel patterns away from private car use [86]. Otherwise, the travel habits of the residents may be affected in that they become dependent on cars for transportation. This was demonstrated in Hammarby Sjöstad and raised as a concern in the evaluation of the district as an aspect that should be improved and incorporated in future urban development projects [16].

Restricted parking was initially introduced in Hammarby Sjöstad, but the situation changed after pressure from the residents to match the parking allocation in other parts of Stockholm (Pandis and Brandt 2011) [16]. A growing preference among the residents to use private cars led Hammarby Sjöstad to raise its car parking spaces from 0.4 to 0.7 per apartment. Similar concerns can be raised about the car parking restrictions within SRS. Further, there is risk that residents will park outside the district, which is likely to have implications for the surrounding parts not concerned with the stricter parking regulations set within SRS (Holmstedt, Brandt and Robert 2017) [47].

Nevertheless, SRS has made special efforts targeting behavioral change among citizens as equally crucial as ensuring infrastructural provisions for mobility and accessibility within the district [66]. To further encourage residents within SRS to avoid using private cars, parking restrictions are planned whereby the parking amount within the area will be limited to 0.5 parking spaces per apartment [47]. There are also plans to provide a higher than average number of cycle parking spaces, 2.2 places per apartment [70]. The area is also planned to be connected with the rest of the city with an extension of a central city tramline [85]. Nonetheless, the newly opened highway Norra länken, which is one of Sweden's largest ever road development projects, raises the question whether it is possible to successfully implement a sustainable transport system within the area in terms of reducing car use, as the proximity to this new road can encourage transportation by car through ease of access to the road network [47].

In addition, examples of smart transport solutions adopted in Stockholm include automatic provision of priority to public transport: the use of a smart traffic light system for determining the movement of priorities of different types of transport (public transport, buses with many passengers, emergency services, etc.). By 2040, the city aims to ensure max 3 min waiting time for public transport and 100% of Stockholm public transport to be driverless [87].

Similar to SRS, the backbone of the transport system in Western Harbor, as a climate-friendly district, is walking, cycling, and public transport. The Western Harbor area is based on environmentally sound transport approach by being planned with lots of different types of services and recreation so as to reduce the need for transport, and the use of environmentally friendly modes of transport is encouraged and pedestrians and bicycles have priority in the area [76]. The public spaces, mostly closed to cars, in Western Harbor provide a range of opportunities for cycling and walking along pleasant routes. According to Malmö City (2006, pp. 3, 6) [76], 'Cars are not allowed to dominate, pedestrians rule ... Bus stops are within as distance of 300 m from the flats. The bus service which connects with several of the main central points in town run in seven minute intervals.' Bus ridership is in the Bo01 area about the same as the city average [88], and the distance to the bus stop is within 1500 feet, with buses operating on a seven-minute schedule [76]. As part of the city target of reducing car journeys by Malmö residents to 30%, Western Harbor's long-term objective is for walking, cycling, and public transport to account for at least 70% of journeys to work and 75% of residents' journeys by 2031 [69]. In the City of Malmö, 30% of all trips are by bicycle and 40% of trips to work or school are by bicycle [89].

Different surface areas are required for the same number of travelers, depending on the means of transport (cycle, bus, car, etc.). In this respect, the City of Malmö (2015) [69] has identified ten initiatives (Table 5) and developed strategies for how the work should be continued.

Table 5. Ten initiatives in influencing behavior and shaping physical structure. Source: Malmö City (2015) [69].

Influencing Behavior, and Dialogue	A Physical Structure for Walking, Cycling, and Public Transport
1. Communicate the city's approach to transport and spread information, 2. Intensify mobility management initiatives linked to companies and workplaces, 3. Intensify information and mobility management initiatives linked to housing, 4. Develop ways of providing information about sustainable travel to visitors, 5. Participate actively in developers' environmental certification,	6. Cycling must be visible and prioritized, 7. Short, safe and pedestrian-friendly, 8. Fast, high-capacity public transport, 9. Vehicle traffic on human terms, and 10. Multi-storey car parks as the parking solution.

Multi-storey car parks as the parking solution was proposed as a result of the concern raised in the Bo01 area. The affluent lifestyles of many inhabitants in the Bo01 area have led to higher car ownership than anticipated, which subsequently resulted in building a multi-storey carpark in the area of Western Harbor [69]. It was a challenge to determine the amount of space needed for parking, as the demand for parking was underestimated. Regardless, parking provision per household is still low compared to Malmö's average: a ratio of 0.7 versus ratio of 1.1. In addition, the City of Malmö has successfully implemented pilot projects with car and cycle pools in partnership with property owners and developers in Western Harbor, but the rentable electric car scheme was withdrawn in the Bo01 area, as the fleet that was available to residents never took off [69].

4.1.3. Green Structure—Green and Water Areas

The municipalities of Stockholm and Malmö operate with the concept of 'green structure' in their plans. This concept comprises larger green spaces, waterways and streams, shorelines, parks, natural and agricultural land, and forests as one common structure. Green space entails the areas of nature found in the urban landscape, and includes trees, grassy patches, water features, flowerbeds, and rock gardens. Stockholm is a city with abundant green and water. Over 90% of Stockholm's population live within 300 m^2 of a green area, and over 10% of Stockholm's surface is water [61]. Green zones and parks represent 40% of the City of Stockholm [67].

SRS is located between the inner city and nature [65]. A key strategy for sustainable urban development underlying the sustainability program for SRS is 'let nature do the work.' In this regard, in the planning process for SRS, multi-functional green structure has been designed 'to provide important ecosystem services, such as flood protection, temperature regulation, recreation, and biodiversity. Parks, courtyards, and other spaces form a green structure that helps to create a more resilient urban district' [66]. According to the sustainability report for SRS [66,73], the results achieved in 2017 in connection with the strategy in question are presented in Table 6:

Table 6. The achieved results of the green strategy in 2017.

• In total, 100% of apartments have access to a park and natural environment within 200 meters. • In total, 5.5 ha of parks has been built and divided between 2500 apartments. • In total, there are 447 newly planted trees and 25 tree species. • In total, there is 13.500 m^2 of green roofs, which corresponds to two football fields. • In total, there is 29.500 m^2 of green courtyards, which corresponds to four football fields. • Parks correspond to seven football fields.

A great deal of attention in Western Harbor, Bo01, has been given to highly diverse green spaces and biodiversity. Rainwater is diverted through aboveground gutters surrounding each building as part of public space design, and the drainage system is designed to be aesthetically pleasing, with waterfalls, canals, ponds, and various elements for purifying and buffering the water. Rainwater travels through green roofs, into ponds in the courtyards, where it is partially cleaned by the ora, and public spaces and is then transported into open canals along the streets to run out into the sea [76]. Rainwater is not channeled in pipes under the ground, i.e., cannot infiltrate into the ground. The green roofs help reduce the amount of rainwater to be drained. As stated by Malmö City (2015, p. 14) [69], 'the journey of the rainwater begins up on the roofs, where it is slowed down by green roofs, a smart solution used on many roofs in Western Harbor.' The objective set by Malmö City (2015) [69] is for all service water to be dealt with locally on site, and the area is moreover designed to deal with climate change and heavier rainfall in the future.

The City of Malmö uses what is called 'green space factor,' a planning instrument introduced in 2001 in connection with the Bo01 housing fair that guarantees a certain volume of greenery in residential courtyards. This instrument is now being used in the city's new construction projects. The General Plan for Malmö states that, 'Green space factor is a tool for ensuring that green qualities are achieved in connection with construction. Green space factor can be used where appropriate and can be developed to be more applicable in different contexts. The aim is to contribute to good living conditions for humans, animals and plants'. A green space factor system ensures that the solution should involve not only the greening of the inner courtyards with plenty of vegetation and ponds, but also green roofs and climbing plants on the walls (Malmö City 2006) [76]. The positive contribution to the urban environment made by the greenery and water resulted from the application of green space factor pertains to ecosystem services, such as recreation, reduced risks of flooding, improved local climate, and noise reduction [76]. The General Plan states that: 'Ecosystem services must be valued, taken into consideration and reinforced in urban planning, maintenance, and management so that their values and functions do not deteriorate'. Furthermore, to promote biodiversity in Western Harbor, green space factor is supplemented with 'green points,' a list of 35 wide-ranging environmental measures were implemented in Bo01—at least 10 of which were to be implemented in every residential courtyard—e.g., bat nesting boxes, butterfly flower beds, country gardens, soil depth to grow vegetables, and so forth [69,76]). Surveys of the residents indicate, as stated by Austin (2013, p. 49) [90], 'great satisfaction with the neighborhood and the units with the exception of some consternation about a presumption by the citizens of Malmö that public funds were expended to provide facilities for wealthy residents'.

In both SRS and Western Harbor, green areas are valued highly and recognized as important for the preservation of nature's own integrity as well as a significant recreational factor for the inhabitants of the districts. Green space is particularly associated with health and recreation as part of the quality of life. As stated by Malmö City [76] (p. 3), 'research shows that close contact with green areas, sun, and water make people healthier, both physically and mentally. Beauty . . . also has a proven positive effect on health. These research results were all taken into account by the planners.' One local planner from Stockholm Municipality said, 'Green space is highly appreciated in the local area due to its health and recreational benefits, and the SRS diverse greenery and water features are increasingly attracting people to settle in the district.' The SRS area is surrounded by perfect green and water view. It lies next door to the Royal National City Park. So, it is being developed in direct proximity to Stockholm's only urban national park, which is classified as a protected area both with regard to its specific and sensitive flora and fauna and to its cultural heritage [91]. It also runs along the waterline of the Baltic Sea. It is being transformed into a livable waterfront district, providing favorable conditions for residents to live and work in good health and with the quality of life. One of the goals of the plan for SRS is to use the waterfront footpath and railway park as linkages to several landscape nodes. The waterfront area offers plaza, green space, park, and promenade, allowing for a variety of activities to take place. According to one expert in SRS development, 'the waterfront area provides great opportunities and its offerings are crucial to encourage social mix of residents and social interaction, as well as a mixed use of functions. Therefore, the planning aims to enhance accesses to this area given the radial layout of urban form.'

4.2. Economic Sustainability

Generally, while the environmental concerns remain a key driver of the eco-city projects and initiatives, they are also mobilized in the pursuit of economic ends. Indeed, economic aspects and issues in SRS and Western Harbor are of particular emphasis as the districts seek to be a vehicle for developing new renewable energy and energy efficiency technologies, as well as to be attractive and vibrant as built environments. Accordingly, environmental sustainability is perceived as a source of economic development. The plans and publicity materials of SRS and Western Harbor projects led by the state and private sector actors contain innovative technologies and ambitious targets, attractive designs, modern architecture, and green areas and parks for recreation to advertise their 'eco-ness.'

4.2.1. Mixed Land Use and Attractiveness

Land use refers to the distribution of functions and activities across space, grouped into different categories. Widely recognized for its important role in achieving sustainable urban forms, mixed land use denotes the diversity and proximity of compatible land uses, a form of cross-sectional residential, commercial, institutional, and cultural infrastructures associated with living, working, and service and amenity provisioning. As a preferred typology in sustainable urban planning and development, diversity, which overlaps with mixed land use and the variety of land uses, entails building densities, housing for all income groups through inclusionary zoning, a variety of housing types, job–housing balances, household sizes and structures, cultural diversity, and age groups, thereby representing the socio-cultural context of the compact city. Indeed, diversity has been used interchangeably with social mix (i.e., housing types and options, demographics, lifestyles, etc.) in the literature. The mixed land use and social mix approaches are an important part of the planning and development strategies of SRS and Western Harbor, aiming towards a lively and long-run sustainable city with a balance between environmental, economic, and social factors. As supported by one architect from the Municipality of Malmö, 'the diversity of functions and architectures of the district gives a good base for services, retail trade, and public transport, and also induces people to live and work in the area.' One expert of SRS development said, 'mixed-land use has not only economic benefits of sustainability, but also environmental and social benefits through sustainable travel behavior and equal access to services and facilities respectively.'

Strong support for the sustainable development advantages of a diverse and vibrant built environment—a mixed-use city—is well reflected in a series of debates with politicians and experts and open community meetings with respect to Stockholm and Malmö's future and key urban development initiatives [67,75]. This is expressed relatively in the same manner as to SRS and Western Harbor (Table 7).

Table 7. Mixed land use features in SRS and Western Harbor.

Districts	Mixed Land Use Features
SRS	A key strategy for sustainable urban development underlying the sustainability program for SRS is 'vibrant city' (Stockholm City 2009) [65]. The program for SRS aims at a mix of housing, offices, shops, amenities, and public services and facilities combined with well-designed, varied public spaces—streets, parks, and squares—as important meeting places that create conditions for a lively atmosphere between the buildings [66]. It was planned that: 'Quayside walkways will be laid out along the port areas, with offices, restaurants, bars, and shops [in addition to conference centers, theaters, gyms, and hotels] helping to create a mixed urban development full of life and activity . . . The dynamic of the city will be reflected in the diversity of living accommodation and the range of amenities, culture, and entertainment. Housing, amenities, and public spaces will be distinguished by accessibility and modernity' [65] (pp. 16, 18).
Western Harbor	Western Harbor is 'a district with a mixture of housing, services, industries, workplaces, education, and recreation. The district has a unique, attractive location with urban and natural features; it is within walking distance of the inner city, has good transport links. . . . By continuing to develop these qualities and building a mixed city, it will be possible to link Western Harbor to the central parts of Malmö' [69] (p. 9).

An attractiveness discourse prevails in SRS and Western Harbor and is strongly linked to mixed land use and diversity. Creating an attractive and safe district with vibrant life is thus one of the key goals of the planning strategies for the two districts. A set of statements describing attractiveness and safety from the Master plans for the two districts is presented in Table 8.

Table 8. Attractiveness and safety in SRS and Western Harbor.

Districts	Attractiveness and Safety
SRS	A variety of spaces is planned in SRS—intense, peaceful, and quiet settings, and busy walkways (Stockholm City 2019) [66]. SRS entails 'a diverse offering of homes and office space [that] will attract a multitude of inhabitants and businesses . . . Diversity leads to freedom of choice. People living in the district will be able to select welfare services to meet their needs and requirements, SRS will have space for everyone' [65] (p. 23). The results achieved in 2017 show, according to the sustainability report for SRS [66,73], that 91% feel safe in SRS compared with an average of 71 percent for the City of Stockholm. The amalgam of land use forms a network that connects both internally and with surrounding areas, favoring of safety [66].
Western Harbor	One planner from Malmö Municipality said, 'Greater diversity gives a district life that is attractive and creates a feeling of security'. Western Harbor strives to provide a safe district where people feel a sense of belonging and security, with access to services and public spaces and thus opportunities to meet. 'The urban environment should offer natural meeting points and a well-balanced mix of housing, activities, education, service, and green areas. Human needs for a variety of sensory impressions like beauty, human proportion, nature, water, contact, and safety should be met' [76], (p. 7).

Accessibility is a crucial aspect in encouraging social interaction among the local inhabitants, and access to everyday commodities within a walking distance is a key issue in both Western Harbor and SRS. Both districts strive to provide greater opportunities to manage daily life on foot, by bike, and by public transport thanks to the proximity to shops, services, facilities, and workplaces. This reduces the needs for long-distant transport, as more errands can be run by walking, cycling, or public transport, and more people will have an easier day-to-day life. Both districts highlight their commitment for prioritizing infrastructure provisions for walking, cycling, and public transport, and also set parking standards—cars per apartment unit and bikes per apartment. One of the smart sustainable solutions implemented by SRS is street spaces for pedestrians, cyclists, and public transport with appropriate infrastructure for electrical vehicles, car pools, and bicycle parking [74].

4.2.2. Business Development

Sweden ranks in the top two in the European Union Innovation Union Scoreboard, and Stockholm's national competitiveness and performance is very high. SRS as a new urban district is one example that reflects the measures the City of Stockholm is taking to attract investments, business ventures, and visitors, especially in relation to green technologies and innovative solutions. The vision of Stockholm is to be, by the year 2030, a world-class dynamic and innovative economy that successfully competes with products and services in the global marketplace, and that is characterized by knowledge-based businesses; high innovation; and unique collaboration between businesses, educational institutions, and research facilities [65].The City of Stockholm's green-tech, innovation-led, diversified economy is a result of a long-term and wide-ranging approach to Swedish economic development that involves partnerships between government, academia, and industry. Stockholm improves the environmental performance towards the low-carbon economic development, which has made it a green economy pioneer. It is one of the world's cleanest capitals in the world and has a long history of environmental work. It was the first city to be granted the European Union's Green Capital award by the European Commission in 2010 [62] because of its high environmental standards and ambitious goals for further environmental improvement, to reiterate. In addition, Stockholm demonstrates high economic growth along with a high employment rate. The financial component of Stockholm Smart City strategy includes the following [87]:

- An attractive, innovative and growing city, with the perspective of making an investment or establishing a business;
- A central node in a global network of successful cities;
- One of the best start-up scenes in the world;
- Develops and grows through entrepreneurship and intrapreneurship in digitalization and new technologies;
- Attracts talent and visitors, both international and national;
- Manages its public operations cost efficiently by making full use of digitalization and new technologies.

Green and Environmental Innovation

One of the strengths of the SRS project in terms of the environment that gives it an advantage over other projects lies in cutting-edge green-tech innovations. SRS is expected to contribute substantially to the economic growth of Stockholm's potential as an innovation hub (with Ericsson, ABB, Fortum, and Electrolux). The two main economic growth sectors in SRS are the innovation sector and the services sector. With respect to the former, in particular the innovation center for sustainable technology, the sustainability initiatives will become the focus point for the district to showcase the sustainable development lifestyles. As to the latter, which remains specific to the district and thus may not be generalized to other eco-city districts, the cruise port is expected to expand the tourism industry and related services, as well as to boost regional business links. This aspect relates to the argument that cities and districts are fully dependent on the surrounding environments.

SRS aims to take the lead in realizing the latest innovations within environmental technology and sustainable development, and affords particularly great opportunities for climate-adapted and future-oriented development, from pioneering energy-efficient technical solutions in building and infrastructure to the development of smart electricity networks that enable local production and distribution of electricity [65]. According to the environmental and sustainability program for

SRS [70], the innovation center in SRS will feature the latest developments in clean and environmental technologies and show how related solutions are being tested and applied, and SRS will serve as platform for presenting the area to the public and interested parties and an important showcase to the outside world. It will also serve as an international meeting place where the city, the business community, and research institutions work together to profile and demonstrate Swedish know-how in urban sustainability. The formal organization in the SRS project works in parallel with the SRS Innovation Arena, which involves industry experts, businesses, and citizens, to build up practical knowledge [48]. However, looking at the economic growth achievement of Hammarby Sjöstad, the project has provided opportunities to many development and construction companies as well as benefits to green-tech companies, and also the new green-tech and skills developed for the site have been exported to wider markets in Sweden and abroad.

The transformation of Malmö from a typical industrial city to knowledge city can be seen more clearly in Western Harbor than in any other part of Malmö. The old shipyard area has become Malmö's new center for IT companies, and many high-tech, knowledge-intensive service companies have moved in the area (Malmö City 2015) [69]. The proximity between companies and Malmö University and its innovation centers in the Western Harbor area means that partnerships between these are well established. There are also innovative industries such as MINC (Malmö Inkubator), Cleantech City, and MECK (Media Evolution City) in the area. There exist approximately 300 companies in the area that together employ approximately 8000 people [69].

A great deal of the positive experience gained from the development of the initial site of Bo01 is of economic nature, especially the success of the Bo01 Project as a marketing tool for the City of Malmö in terms of attracting new investments, ventures, and international interests. Bo01 is a well-known internationally leading example of sustainable urban development, and an initiative that has received a number of awards, attracted study visits from all over the world, and been extremely important to the local work for ecologically sustainable urban development in the city of Malmö [69]. It has been a catalyst for attracting further development initiatives in the city, and much has been learned from it that is directly being applied to further development in the Western Harbor area. The district's planners have created an unusual laboratory, resulting in an exceptionally pleasant district thanks to clean technologies and the great deal of architectural diversity without the usual restrictions. These aspects have made the area an example for other urban development projects in Sweden and in other parts of the world [69]. Proved additionally to be a success is the incorporation of green components in the individual projects beyond basic landscaping, as well as the collaboration on and achievement of a shared vision of sustainability among companies, organizations, and institutions with different goals and interests.

Research and Development and Public and Private Partnerships

Another related dimension of economic sustainability is research and development (R&D) opportunities created in light of the planning, development, and management of SRS in the medium and long term. There are 20 R&D projects (e.g., the smart grid project, ICT for sustainability, climate+ development program, sustainable lifestyles project, evaluation model research program, etc.) currently active, which are conducted in collaboration with the academic community, research institutes, and businesses [66]. There is strong synergy among public and private sector, including the industry community and research institutions to finance innovations, and a robust social capital and trust in district governance. In their article 'Governing the Smart Sustainable City: The case of the Stockholm Royal Seaport,' Kramers, Wangel and Höjer (2016, p. 108) [48] state that the SRS project 'represents the joint collaboration effort of citizens, construction developers, waste, water, and energy utilities, as well as the city departments, to meet the vision of real-time feedback as outlined in the city's sustainability program for the SRS.'

Research is key in the development of Western Harbor since Phase 1 2001, the Bo01 Project, in terms of scientific evaluation related to urban sustainable development and the use of results in future projects, both locally and in other parts of the world [76]. The evaluation work pertaining to Bo01 involves 10 universities and colleges, and the area receives study visits from all parts of the world. A key part of such work includes the infrastructure and function of the technical systems, including waste disposal system and energy supply, as well as the perception of housing and surroundings by residents [76]. Like SRS, there is a number of ongoing research studies within all areas of priority: traffic, energy, green structure and storm water, building and living, recycling, environmental information and education, and sustainable development [76].

The Line–Atlas Project entails an attractive urban environment that promotes innovation, research, development, interaction, and economic growth. It is an urban development project that focuses on modern workplaces in a networking city. It extends between Central Station and Dockan and comprises more than 300 businesses and institutions, 6000 employees, and 10,000 students in a business community that is already active [69]. With this project, businesses and workplaces are promoted by developing urban life, urban space, and urban environment. According to the updated plan for Western Harbor [69], the vision is to create the most attractive, modern workplaces; the world's most innovative business environment; and a strong community of businesses, institutions, and employees. In addition, the Line Project emphasizes the individual business and the community—sharing economy—by using and transforming premises, buildings, and spaces, and also examines the development opportunities along its route, meeting places, and other urban facilities [69]. In fact, the city district's increasing population creates a need for more workplaces and housing, and this population makes use of the supply of businesses, services, and facilities.

4.3. Social Sustainability

Much of the literature on the City of Stockholm points to its greater focus on the environmental and economic goals of sustainability than the social goals of sustainability. The planning practice in Stockholm gives greater priority to ecological sustainability than to social sustainability [91]. The social goals are merely general descriptions and usually represented in eco-district strategies on a discursive level. The strong emphasis on the environment and economic dimensions of sustainability is indeed clearly reflected in the environmental and sustainability program for SRS ([66,70]). This indicates unequal attention to social sustainability goals. Conversely, the social, economic and environmental goals of sustainability are at the core of the continued development of Malmö, and the city strives to balance between the three dimensions of sustainability. As stated by Malmö City (2014) [75], 'Social divides in Malmö are to be healed and the city united—barriers are to be broken and inequalities are to be reduced through considered social investment. In the same way that we invest in the physical infrastructure then we must invest in Malmö's human capital.' The outcome of the holistic approach to sustainability adopted in the Bo01 Project was the quality of aesthetics and social opportunities, and the project supports human, psychological, and physical health through ready access to open space, walkability in neighborhoods, and social interaction [90].

4.3.1. Physical Planning and Social Interaction

Physical planning can contribute to a more socially cohesive district. Therefore, Western Harbor's vision and planning policy promotes diverse and mixed-use patterns to reduce socio-economic segregation and increase livability. The outcomes of the Bo01 project entailed outstanding aesthetics in the plan and the individual and green components, as well as spaces that foster social interactions at the block, neighborhood, and city scales [90]. Many social spaces are designed within a diverse landscape, as approximately 50% of the Bo01 area is open space. Malmö City (2014) [75] argues that the physical environment as a framework for social interaction is a basic condition of life in the city, as spatial arrangements and designs affect the movements, residential patterns, and habits of citizens. In other words, a sustainable district must provide opportunities for people to interact with each other and carry out cultural activities through varying interior open spaces caused by the structure and the social interaction. The City of Malmö aims to create an exciting structural mix of individually designed streets, pedestrian walks, alleyways, and open squares in the area of Western Harbor [76]. In connection with the continuous development of Western Harbor, the city moreover aims to create an urban environment with a well-balanced mix of housing, activities, education, service, and green areas [76].

One way of evening out existing economic and social differences in both Western Harbor and SRS is ensuring that all parts of the districts have good physical links within and between the parts. As stated in the Comprehensive Plan for Stockholm City, neighborhoods will be linked and physical barriers isolating certain areas will be removed by developing new areas, improving public transportation, and providing more public spaces [67]. The development strategy aims at a closely connected district using physical planning as a tool. Similarly, Malmö City (2014) [75] states that links must be forged between the communities in different part of the city to heal a segregated Malmö, and argues that the barriers will be lifted and mental distances reduced by redesigning trunk roads and other main roads into urban high streets.

4.3.2. Social Cohesion

Although social cohesion is a multi-faceted process, in this context, it entails task relations, perceived unity, and social engagement. In particular, involving local communities in planning and decision-making processes is significant for residents to have a say in the development and management of SRS. Giving voice and influence should be done before and during the planning stage. According to the program for SRS, local people and some potential residents will be invited to attend a series of planning workshops, e.g., exploration of strategic options and community planning sessions. In terms of the results achieved in 2017, as stated by Stockholm City [66,73], the digital dialogue in Värtahamnen engaged 750 participants and over 100 suggestions were received, and 350 people attended a capacity development seminar in 2017 and approximately 1100 people since the start. In SRS, there has been a citizen network dialogue with information dissemination concerning different issues. Including people in consultation and idea-generation processes is an effective approach to hear their voice and then consider their advice and manage their concerns. As stated by Kramers, Wangel and Höjer (2016) [48], the intent of the dialogue processes adopted by the municipality to create an active dialogue with the citizens is to gather input on their needs and demands, which in the case of SRS focus more on bus timing, playgrounds for the children, parking lots, the reliability of different ICT systems (e.g., parking meters), and mobile coverage indoors.

4.3.3. Citizen Participation

One of the key strategies of sustainable urban development underlying the program for SRS is 'participation and consultation.' This is of crucial importance for improving social cohesion. In this respect, Stockholm City (2019) [66] argues that the sustainable city can only be created by cooperation between residents and businesses, the city's administrations and companies, property owners, academia, and other stakeholders. These parties are engaged and invited to take part in dialogue in order to shape and manage SRS together, especially residents, as in any planning process. However, the interview revealed that there is a lack of structures for collaboration between different stakeholders in SRS within the city departments. It is vital that all the involved stakeholders have willingness and interest in collaborating and understanding their role, especially from a holistic perspective, as the planning and development of a new district engage numerous stakeholders that need to be aware of the overall end goals in order to avoid counterproductive decisions and related consequences [47].

4.3.4. Socio-Economic and Spatial Segregation

From a critical perspective, currently, there is a division into 'immigrant' and 'native Swedish' populations in the Cities of Stockholm and Malmö, coupled with the persistent socio-economic spatial segregation, which is highly problematic. Stockholm has segregated residential areas, where some city districts are predominately inhabited by people with low socio-economic status, while others are inhabited by people with higher social status and income [67]. Also stated in the Comprehensive Plan for Malmö is that the city is partly characterized by segregation and social disparity, manifested in the large differences in living standards and public health between different city districts [75]. The city is working on and investing in breaking these trends in order to unlock the full potential offered by the city's population and cultural structure, nevertheless.

There are housing shortages and unfordable prices in SRS and Western Harbor, and excessive regulations slow housing development, market-oriented rent setting in the Cities of Stockholm and Malmö. Even though the two districts continue facing housing shortages, their development has been going on in slow pace. The interview revealed that there was a lack of affordable housing incorporated in the site of Bo01, and the residents had to cope with hefty heating bills because the dwellings have large areas of glass. The energy efficiency goals set in Bo01 were not met because the energy budget of the proposed buildings was not calculated properly. Further, the cost of the residential units was one of the missteps of the Bo01 Project, being too high to serve low- and moderate-income residents, and the increased demand for living in Bo01 lead to a double increase in the prices of the units until 2007. As a consequence, the residents of Bo01 constitute a homogenous group—healthy, white residents, notwithstanding the Bo01 project's aim to create mixed forms of housing to reduce the risk of segregation (e.g., ghetto formation) [69]. Regardless, as one local planner said, 'the lack of diversity is due to the unfordable housing prices in the district, e.g., a price of a flat is more than twice the national average price. Nonetheless, the city of Malmö has been working on developing Bo02 with greater affordable housing.' Typical of the City of Malmo is a mix of residents of various socio-economic level precluded by the cost of the residential units in the Bo01 area [90]. In connection with the continuous development of Western Harbor, the City of Malmö (2006) [76] aims also to create housing of mixed forms, providing different people with the opportunity to settle in the district. Indeed, tenant-owner flats and rented dwellings have been added to the recently developed areas, with a planning focused greatly on safety and security aspects via the design of meeting places [69]. There are three recent development projects for housing in Western Harbor concerned with housing mix [69]. These are presented in Table 9.

Table 9. Development projects for mixture of housing in Western Harbor.

• Flagghusen consists of 626 dwellings—of which, 62% are rented and the rest are tenant-owner flats. • Fullriggaren comprises approximately 630 homes, and 85% of dwellings are rented and the remainder are tenant-owner or owner-occupied flats. • Kappseglaren comprises approximately 320 dwellings. 70% are rented and the remainder are tenant-owner flats or owner-occupied flats.

5. Discussion

The findings showed that the eco-city district models of SRS and Western Harbor involve mainly design and technology, supported with behavioral change, as key strategies and solutions for achieving urban sustainability. Design encompasses greening, passive solar houses, sustainable transportation, mixed land use, and diversity. And technology comprises green technologies, energy efficiency technologies, and waste management systems. Design contributes to the three goals of sustainability, and technology contributes mostly to the environmental and economic goals of sustainability. Behavioral change is associated with sustainable travel, waste separation, and energy consumption.

Taking the above into consideration, the eco-city district model entails an integrated set of urban-ecological proposals supported by land use, environmental, economic, social, and institutional policies that is directed towards managing urban spaces to achieve sustainability. The eco-city district model as practiced by SRS and Western Harbor is justified by its ability to contribute, albeit not equally, to the environmental, economic, and social goals of sustainability. This corresponds to the results obtained from other studies (e.g., [17,43,92]). Furthermore, at the core of the eco-city district model is the clear synergy between the underlying strategies in terms of their cooperation to produce combined effects greater than the sum of their separate effects with regard to the benefits of sustainability as to its tripartite composition. For example, behavioral change facilitates waste management collecting system, which in turn affects the output of the bio-fueled CHP system and thus save energy, e.g., electricity produced locally by renewables, for other uses. Further, the availability and quality of the public transport infrastructure is a determinant factor for mixed land use development projects, which in turn contributes to creating urban environments full of social vitality and economic activity, as well as to improving infrastructural provisions for public transport.

Concerning environmental sustainability, the two city districts aim to conserve energy and decrease the demand for it through renewable sources—sun, wind, and water, bio-fueled CHP system, passive solar houses, energy efficiency processes (smart grid), and waste management systems; to reduce material resources through sustainable construction materials and waste management processes; to decrease travel needs and shorten distances through sustainable transportation, namely walking, cycling, public transport, and car pools; and to reduce the pressure on green areas, ecosystem services, and biodiversity through green structure and green factor planning tools. This is consistent with the results from other studies (e.g., [9,16,47,90]).

The energy sector—including transport—produces the largest share of the world's emissions of greenhouse gases (GHGs). Therefore, when the energy system is based completely on renewable resources, coupled with passive solar design (sustainable buildings), smart technologies (energy efficient buildings), sustainable waste management and transportation, the reduction of emissions is very significant. This bold strategy will make it possible for the two city districts to become climate positive, and also pave the way for phasing in renewable energy sources and phasing out fossil fuels and potentially support the entire geographical area of the Cities of Stockholm and Malmö with renewable energy by 2030. In regard to passive solar design, many studies have demonstrated and discussed its environmental benefits (e.g., [6,93–96]) related to building heat gains and losses, warming and cooling pressures, heat storage and discharge, emissivity, air and noise pollution reduction, and so forth. Concerning waste management, Marcotullio (2007) [97] argues that sustainable systems create the infrastructure to naturally process sewage waste, grey water, and storm runoff on site, in addition to preventing flooding on the urban hardscape and utilizing wastewater to fertilize and water gardens. Further, the eco-city manages an ecologically beneficial waste management system that promotes recycling and reuse to create a zero-waste system [9].

In relation to sustainable transportation, when the collective transports are powered by electricity that is produced by biofuel or solar energy, the reduction of emissions is significant. Transport is the greatest issue for environmental debates related to urban form (e.g., [6,98,99]), and is key for achieving the status of the eco-city [100]. Of importance also is the concentration of functions and activities in the two city districts that serve to, in addition to fortifying the economy, reduce the car use in favor of public transport and bike use. However, in order to implement the use of collective modes, more holistic strategic policies have to be put in practice to discourage car use. This should go beyond the increase in parking levies, the reduction of parking spaces, the increase in road pricing to make car use less attractive to include concrete incentives from public transport and bike use, travel behavior influence, and mobility management. As regards the advantages of sustainable transportation, it operates the transport system at maximum efficiency, provides favorable conditions for energy-efficient forms of transport, limits CO_2 emissions, allows equitable accessibility to services and facilities, promotes renewable energy sources, decreases travel needs and costs, minimizes land use, and supports a vibrant economy [101].

With respect to greening, green space has the ability to contribute positively to key agendas of sustainability in urban areas [102]. It provides recreational opportunities, ameliorates the physical urban environment by removing CO_2 emissions and other toxins from the air, enhances the aesthetics of urban areas and thus make them more pleasant, increases the urban image and economic attractiveness, helps to control storm runoff, creates the conditions for more ora and fauna, and enhances biodiversity [101]. However, green space has been a subject of debate when it comes to the development and redevelopment of urban areas. In this respect, the argument that the urban form will reduce the pressure on green areas, ecosystem services, and biodiversity is less certain. While the goal of protecting large green areas outside the development areas finds support in the two city districts, it is more uncertain when it comes to green areas located in or close to the urban fabric given the potential enticing opportunities for the new development projects to strengthen the economic goals of sustainability through eco-city strategies. In relation to this, SRS is being developed in direct proximity to the Royal National City Park, a protected area as to its specific and sensitive flora and fauna and to its cultural heritage [103]. The concern that the park as a sensitive area would be exposed to degradation in terms of quality and land [103] has been incorporated into the environmental program for SRS [70]. However, the issue of redeveloping this land is not discussed within the program, and it is important to consider an alternative approach that can assist in safeguarding the flora and fauna [47].

Furthermore, the two city districts tend to exhibit some differences in the way they practice ecological urbanism, especially in terms of sustainable systems and greening. This is due to their physical, architectural, geographical, historical, as well as socio-political specificities, which shape eco-city planning practices and development strategies. Indeed, there are great differences between cities in terms of their urban form as to its key constituting elements (e.g., [104]), as well as in terms of their ecological ambitions (e.g., [30]). Moreover, in their study, which aims to uncover the diversity underneath the various uses of the eco-city as a concept and to determine the extent of divergence in the way the eco-city projects conceive of what an eco-city should be, Rapoport and Vernay (2011) [17] conclude that there is a great deal of diversity among the projects considered to be eco-cities, and argue that it is better to think of the eco-city as an objective which can be achieved through various ways. This implies that there is no single vision for an eco-city district, and that the local opportunities and constraints need to be addressed in a more integrated approach.

On the whole, the focus in the two city districts is on the use of technology and design as main solutions to reach environmental targets. Production focused solutions incorporate technologies to generate renewable energy, and consumption focused solutions use smart technology and passive solar houses to decrease the demand for energy resources. This is consistent with the results from other studies (e.g., [16,17]). Additionally, the inhabitants in Western Harbor and SRS are encouraged to change their behavior to live more sustainably, and in this context, making sustainable living effortless for residents is key. The latter is in agreement with the results from other studies (e.g., [16,17]). Still, a more focused people-oriented approach should be adopted through encouraging more active engagement among the local residents and involving them at the stages of monitoring the implementation of environmental targets and standards. There is much for SRS to learn from the experience of Hammarby Sjöstad, which has mainly focused on technology-oriented innovations and less on behavioral change of the local residents, who are actually the forefront users of green technologies. As a result, the district has been less successful in fulfilling its previous energy efficiency goal of 60 kWh/m^2, forcing the city to adjust the standard to 100 kWh/ m^2 in 2005 [16]. All in all, the behavior of individuals has become a key facet of environmentally sustainable development.

Of particular importance to highlight as to the technology strategy, especially in regard to SRS, is the role of ICT in reaching environmental targets by lowering energy use and GHG emissions through the optimization of urban systems and services, as well as in environmental planning by enabling more collaboration between diverse stakeholders and empowering citizens. This entails implementing a number of smart approaches pertaining to energy, environment, transportation, and governance. This is consistent with the findings and conclusions from other studies (e.g., [11,12,19,23,82,83,105–108]). There is a wide recognition that advanced ICT constitute a promising response to the challenges of sustainable development due to its tremendous, yet untapped, potential for solving environmental and socio-economic problems. Indeed, a recent research wave has started to focus on smartening up sustainable urban forms by amalgamating the landscapes of and the approaches to sustainable cities and smart cities in a variety of ways in the hopes of reaching the optimal level of sustainability ([2,3]), especially through promoting the 'eco-city' and 'sustainable city' initiatives in their more recent data-driven smart incarnations. Many urban development approaches emphasize the role of big data technologies and their novel applications as an advanced form of ICT in improving sustainability (e.g., [20,21,106,109–111]). Therefore, the field of sustainable urbanism needs to extend its boundaries and broaden its horizons beyond the ambit of the built form and ecological design of cities to include technological innovation opportunities and computational capabilities by unlocking and exploiting the tremendous potential of advanced ICT for advancing sustainability.

With respect to economic sustainability, the two city districts promote mixed land use and diversity as design strategies to improve economic development. Specifically, they aim at a mix of housing, offices, shops, public services and facilities, and amenities combined with public spaces to achieve a vibrant city, full of life and activity. There is a general consensus supported by empirical evidence (e.g., [43,101,112–115]) that the mixture of functions provides a customer basis for commercial activities, enhances commercial properties and housing markets, encourages investments and renewals, creates closeness between citizens and their workplaces, and improves public transportation infrastructure.

Important to point out is that proximity is typically associated with the compact city model under mixed land use strategy, which is used to achieve not only economic benefits of sustainability, but also environmental and social benefits of sustainability (e.g., [101,112,113]). In reference to the eco-city model, Register (2005) [115], who coined the phrase 'access by proximity,' suggests that closeness to important functions and activities, such as educational and cultural facilities and places for meeting and socializing, is necessary to create ecologically healthy cities characterized by walkable centers, transit villages, discontinuous boulevards, and agricultural land close by. Moreover, proximity, how close jobs, amenities, services, and public spaces are to where people live as generally calculated based on the travel time and distance to their homes, strengthens the self-contained local economy feature of the eco-city that obtains resources locally. In this respect, proximity allows the city to be self-sustaining by having everything that people need within the community, including stores, employers, service providers, energy suppliers, waste handlers, and so on [116].

In fact, the eco-city and compact city models have many overlaps between them in their concepts, ideas, and visions, with some distinctive concepts and key differences for each one of them. According to Roseland 1997) and Harvey (2011) [8,9], a desirable eco-city has a well-designed urban layout that promotes walkability, biking, and the use of public transportation system; ensures decent and affordable housing for all socio-economic and ethnic groups (to be discussed as part of social sustainability); and supports future expansion and progress over time. These features are also at the core of the compact city model as the leading paradigm of sustainable urbanism, in addition to other design strategies, namely density, compactness, and mixed land use (see, e.g., [117–124]). The two models also share mixed land use, as discussed earlier, with the difference being that the mixed-use strategy in the eco-city model is not hand in hand with, or strongly linked to, the high-density strategy as in the compact city model. The goal of the next phase of the redevelopment of the Western Harbor has been adjusted to increase the density significantly [90]. The mixed-use strategy involves four dimensions: the social mix, temporal mix of social and physical issues, physical land use mix, as well as economic mix [125].

In view of the above, Bibri and Krogstie (2019) [3] suggest a complete amalgamation of the eco-city with the compact city as both landscapes and approaches based on several arguments distilled from a detailed review and synthesis of the literature on these two prevailing approaches to sustainable urbanism. Similarly, Farr (2008) [126] discusses the combination of the different elements of ecological urbanism, sustainable urban infrastructure, and new urbanism, coupled with making cities walkable, and then extends this integrated approach to close the loop on resource use and to bring everything into the city. This approach is focused on enhancing the quality of life by affording greater accessibility to activities, services, and facilities within a short distance. Farr's perspective on sustainable urbanism is based on bringing everything closer together, being more efficient, using higher quality goods, having everything within walking distance, and closing the loop [127]. However, density and compactness through intensification and how they rely on sustainable transportation are not considered in Farr's approach. In the context of this study, designing an urban district with high population density and intensification is perhaps an aim that is linked to the completion of the two districts.

However, the other key aspects of economic sustainability associated with the two city districts are innovation, research, and public and private sector collaboration. These create an auspicious environment conducive to economic growth and prosperity as manifested in green-tech innovation, production, and export; R&D activities; entrepreneurial and innovation-based startups; industrial and technological investment; job creation and skill development; government, industry, and academia collaboration; and international cooperation. This is in agreement with the results from other studies (e.g., [16,48,90]).

As for social sustainability, the two city districts tie its goals to the creation of an amalgam of social, physical land use, temporal, and economic features. As such, they aim to improve social integration, social cohesion, social capital, and public safety, as well as the quality of life and well-being. More specifically, the two city districts' aims highlight flexible design of housing in terms of types and forms, affordable housing by means of an efficient, careful process, meeting places for social interaction, greater accessibility to services and facilities, ready access to open green and recreational areas, safety and security, housing design enabling residents to remain throughout all stages of life, citizen participation and consultation, and multi-stakeholder cooperation. These are in line with the findings from other studies related to sustainable and ecological urbanism (e.g., [6,16,17,90,101,112,117]). One of the arguments which supports social equity is the possibility to have a better access to services and facilities [128] as well as through the reduction of social segregation [120]. The two city districts are facing some challenges pertaining to the institutionalization of planning practices capable of improving social integration due to the unfordable housing and lack of social mix. In addition, green areas are associated with public health (e.g., [101,112]. Research tends to focus on the health advantages of urban green space [129,130]. With respect to multi-stakeholder cooperation, it relates to the different actors that drive the eco-city district project in terms of what role they play in shaping, developing, and managing it. In this respect, for example, while some solutions have to be adapted to the needs of local residents, which indicates that they play a central role when designing the districts, their involvement in the design process is limited as clearly shown in the planning and development documents. This is also found to hold true by Rapoport and Vernay (2011) [17]. All in all, as stated by the Young Foundation (2011), social sustainability is about 'creating sustainable, successful places that promote wellbeing by understanding what people need from the places they live and work. Social sustainability combines design of the physical realm with design of the social world infrastructure to support social and cultural life, social amenities, systems for citizen engagement and space for people and places to evolve.'

In sum, the empirical data show the contours of a goal hierarchy in eco-city district planning and development. Environmental and some economic concerns are at the top of the goal hierarchy supporting eco-city district strategies. In other words, the environmental goals of sustainability dominate over the economic and social goals of sustainability, notwithstanding the claim about the three dimensions of sustainability being equally important at the discursive level. This is visible by the clear structuration of these goals in the planning and development documents and the associated institutionalization of practices supporting these goals. The environmental dimension of sustainability is at the core of the eco-city [17]. Ecological urbanism/the eco-city focuses more on the natural environment and ecosystems and less on economic and social aspects [18,47]. This is evident from the environmental and sustainability program for SRS, which is a shortcoming as the social and economic aspects are highly important in the context of sustainable cities, whereas Western Harbor is making strong effort to address social and economic issues within the district by implementing new measures to strengthen the influence of social and economic goals over urban development practices. That is, the basis of social and economic knowledge in planning is expanded through institutionalized mapping and registration procedures. While social proposals are usually couched in speculative language in terms of investments, ventures, and employments, the City of Malmo is currently focusing on more socially-oriented projects that have high environmental performances and reduce social inequality and segregation.

The hierarchy of sustainability goals could reflect the challenge of incorporating social and economic issues into a design- and technology-led approach. Perhaps the planners and designers of these districts are simply more knowledgeable about and experienced with how to tackle environmental issues given the long history of environmental work the two cities of Stockholm and Malmö have. The focus in SRS should go beyond the environmental and economic focus to include the social aspects related to the local community. For the two city districts themselves attractiveness does not depend on environment performance and economic prosperity alone. Rather, to attract inhabitants, the two city districts need to develop a broader agenda entailing an amalgam of environmental, economic, and social concerns. And for the two city districts to fully achieve their goal of becoming sustainable urban districts, as they claim, the social and economic aspects of sustainability need to be supported by planning practices and concrete development strategies.

6. Conclusions

Eco-city planning and development has long been one of the preferred responses to the challenges of sustainable development. The city districts of SRS and Western Harbor are seen as exemplary practical initiatives in sustainable urbanism, at national, supranational, and international scales. This study has been carried out as a demonstration endeavor of what these two city districts are renowned for in this regard, with the aim of being exposed to both local and general lessons.

The aim of this study was to examine how the eco-city district model, and especially its three sustainability dimensions, is practiced and justified in urban planning and development. Accordingly, it set out to answer the following two questions: what are the key strategies and solutions of the eco-city district model, and in what ways do they mutually complement one another in terms of producing the expected tripartite value of sustainability? To what extent does the eco-city district model support and contribute to the environmental, economic, and social goals of sustainability?

This study shows that the eco-city district models of SRS and Western Harbor involve mainly design and technology, supported with behavioral change, as key strategies and solutions for achieving urban sustainability. Design encompasses greening, passive solar houses, sustainable transportation, mixed land use, and diversity. And technology comprises green technologies, energy efficiency technologies, and waste management systems. Design contributes to the three goals of sustainability, and technology contributes mostly to the environmental and economic goals of sustainability. Behavioral change is associated with sustainable travel, waste separation, and energy consumption. Moreover, the underlying strategies of the eco-city are not mutually exclusive and thus must take place or exist at the same time in order to guarantee the viability and sustain the performance of the eco-city regarding its contribution to the three goals of sustainability. It can be concluded that the eco-city district is a very complex urban development approach that involves several strategies which are supposed to work together in a synergistic way.

The linkages between the dominant strategies of the eco-city district model and the three goals of sustainability can be outlined as follows:

Environmental sustainability: Managing the natural resources base and ecosystems to meet people's needs, and in ways that lower energy consumption, reduce material use, mitigate pollution, and minimize waste.

1. Sustainable energy systems
    - Local production of electricity—solar energy;
    - 100% locally renewable energy—sun, wind, and water;
    - Bio-fueled CHP system;

- Passive houses;
- A large-scale smart grid;
- Behavioral change.

2. Sustainable waste management
    - Smart waste collecting system;
    - Vacuum waste chutes system;
    - Food waste disposers;
    - Wastewater and sewage treatment system;
    - Behavioral change.
3. Sustainable materials
    - Recycled and reused materials;
    - High performance and resource-effective materials.
4. Sustainable transportation
    - Cycling and walking;
    - Public transport (metro, buses, tram, etc.);
    - Car pools (biogas and electric);
    - Mobility management;
    - Behavioral change.
5. Greening and ecological diversity
    - Multi-functional green structure for ecosystem services;
    - Green factor planning tools.

Economic sustainability: Long-term economic growth without negative environmental and social impacts

1. Mixed land use
    - Physical land use mix (horizontal/spread of facilities, vertical mix of uses, amenity, public space, etc.);
    - Economic mix (business activity, production, consumption, etc.);
    - Some aspects of social mix (housing, demography, lifestyles, visitors, etc.).
2. Economic growth and business development
    - Green-tech innovation;
    - Green-tech production and export;
    - R&D activities;
    - Entrepreneurial and innovation-based startups;
    - Industrial and technological investment;
    - Job creation and skill development;
    - Government, industry, and academia collaboration;
    - International cooperation.

Social sustainability: Improving social justice and well-being

1. Social equity
    - Social integration;
    - Flexible design of housing in terms of types and forms;
    - Affordable housing by means of an efficient, careful process;
    - Greater accessibility to facilities and services.
2. The quality of life
    - Meeting places for social interaction;
    - Ready access to recreational and green areas;
    - Natural surveillance: safety and security;
    - Housing design enabling residents to remain throughout all stages of life.
3. Social cohesion
    - Citizen participation and consultation;
    - Multi-stakeholder cooperation;
    - Well-being of all inhabitants.

In view of the above, the eco-city model as practiced by the two city districts is justified by its ability to contribute to the environmental, economic, and social goals of sustainable development. However, the environmental goals of sustainability dominate over the economic and social goals of sustainability, notwithstanding the claim that the three dimensions of sustainability are equally important at the discursive level. The environmental goals remain at the top of the hierarchy in relation to eco-city development strategies, followed by the economic goals, and then the social goals. Nevertheless, new measures have recently been implemented in Western Harbor that are expected to strengthen their influence over urban development practices. The main issues identified that the two city district are struggling with are socio-economic spatial segregation and unaffordable housing. The SRS program mainly focuses on the environmental aspects, which is a weakness that should be recognized and dealt with as part of ongoing and future urban development endeavors.

More in-depth knowledge on planning and design practices is needed to capture the vision of sustainable urban development, and so too is a deeper understanding of the multi-faceted processes of change to achieve sustainable cities. This entails conceptualizing multiple pathways towards attaining this vision and developing a deeper understanding of the interplay between socio-political and techno-scientific solutions for sustainable urban forms (Williams 2010 and Bibri 2019) [11,13], especially those involving engineering and applied sciences related to big data science and analytics and the underpinning technologies (Bibri 2019) [21,127]. In this regard, the core questions that would potentially broaden our knowledge on how eco-cities can harness their potential through the underlying design strategies and technology innovations and ultimately balance the different dimensions of sustainability in planning and development practices include

- At what stage of the planning process should environmental, economic, and social concerns introduced and even balanced, and what kind of measures are needed to have an effective integration of such concerns early on?
- To what extent can advanced technologies support joined-up planning, a form of integration which enables system-wide sustainability effects to be tracked, understood, and built into the very responses and designs characterizing the operations and functions of the eco-city district, especially in relation to energy, waste, transport, and utilities?

- What kind of advanced technologies are available and can be implemented to make the planning process dynamic based on constantly updated information on the operations and functions of the eco-city district?
- What is the potential of weaving intelligence functions into the fabric of the eco-city district in terms of its institutions to advance sustainability, optimize efficiency, strengthen resilience, improve equity, and enhance the quality of life for citizenry?
- To what extent can emerging technologies leverage the design strategies and the implementation and operation of other urban technologies associated with the eco-city district in ways that enhance and optimize its processes and practices and evaluate its contribution to sustainability?

It is worth pointing that cities are complex systems par excellence and hence dynamically changing and adaptive; self-organizing social networks embedded in space and enabled by urban infrastructure, activities, and services; and developed by multitudinous collective and individual decisions from top–down and bottom–up [61,131]. In view of that, while computational and scientific approaches are very relevant and important for understanding and dealing with the different aspects of urban complexity through big data analytics and the underpinning technologies, they remain inadequate to solve all urban problems ([132,133]). These are often best solved through political/social solutions, citizen participation, and deliberative democracy, rather than technocratic forms of governance [134,135]. Besides, computational and scientific approaches have been criticized for failing to recognize that cities are complex, intricate, multifaceted, and unpredictable systems, full of contestations and intractabilities that are not easily captured or steered, a view which undoubtedly still holds [11,82,106,110,135–137]. Regardless, focusing only on advanced ICT risks to downplay the complexities associated with realizing smart eco-cities. Still, to successfully implement and manage big data technology as an advanced form of ICT for eco-cities requires a holistic perspective so as to be able to identify and manage gaps and conflicts, as well as to harness synergies between different technological components with respect to functionality, ownership, access, and governance.

We hope that this study has produced the kind of results that will be useful in directing further research by providing the grounding for more in-depth investigation on eco-city planning and development, especially in the developed countries that support sustainable development practices. We would particularly like to encourage qualitative research of the kind that we have attempted, which aims to illuminate the key dimensions underlying the eco-city model and the assumptions behind related initiatives. And hence the claims that this model can make urban living more sustainable. The rationale for this is that as the demand for practical ideas from the ecologically advanced nations about how to achieve the requirements of sustainability through eco-city planning and development increases, those initiatives are likely to attract attention from strategic urban actors around the world. Especially, the two districts aim to provide new knowledge and advanced technology about how to build more sustainable cities. Further research should focus on providing the knowledge that these actors will need to make informed decisions about how to achieve the eco-city objectives in their own context. Moreover, as this study has demonstrated that practices, strategies, and goals already exist across the selected city districts, it would be interesting to pursue, in a future research effort, a wider and more varied comparison (involving cities from other Scandinavian and/or European countries) with a view to revealing more general trends in urban planning and development. In addition, a sequel to this work and thus part of related future research is to integrate the eco-city, the compact city, and the smart data-driven city into a novel model for urban planning and development for the purpose of improving, advancing, and maintaining the contribution of sustainable cities to the goals of sustainable development. This is one among many opportunities that can be explored towards new approaches to sustainable urbanism, predicated on the assumption that there are multiple visions of and pathways to achieving sustainable urbanism. Lastly, we believe that the insights gained from this study can help advance the understanding of how the eco-city phenomenon is evolving and adapting to new global shifts.

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Paper 8

The emerging Data–driven Smart City and its Innovative Applied Solutions for Sustainability: The cases of London and Barcelona

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The emerging data–driven Smart City and its innovative applied solutions for sustainability: the cases of London and Barcelona

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Abstract

The big data revolution is heralding an era where instrumentation, datafication, and computation are increasingly pervading the very fabric of cities. Big data technologies have become essential to the functioning of cities. Consequently, urban processes and practices are becoming highly responsive to a form of data-driven urbanism that is the key mode of production for smart cities. Such form is increasingly being directed towards tackling the challenges of sustainability in the light of the escalating urbanization trend. This paper investigates how the emerging data-driven smart city is being practiced and justified in terms of the development and implementation of its innovative applied solutions for sustainability. To illuminate this new urban phenomenon, a descriptive case study is adopted as a qualitative research methodology to examine and compare London and Barcelona as the leading data-driven smart cities in Europe. This study shows that these cities have a high level of the development of applied data-driven technologies, but they slightly differ in the level of the implementation of such technologies in different city systems and domains with respect to sustainability areas. They also moderately differ in the degree of their readiness as to the availability and development level of the competences and infrastructure needed to generate, transmit, process, and analyze large masses of data to extract useful knowledge for enhanced decision making and deep insights pertaining to urban operational functioning, management, and planning in relation to sustainability. London takes the lead as regards the ICT infrastructure and data sources, whereas Barcelona has the best practices in the data-oriented competences, notably horizontal information platforms, operations centers, dashboards, training programs and educational institutes, innovation labs, research centers, and strategic planning offices. This research enhances the scholarly community's current understanding of the new phenomenon of the data-driven city with respect to the untapped synergic potential of the integration of smart urbanism and sustainable urbanism for advancing sustainability in the light of the emerging paradigm of big data computing. No previous work has, to the best of our knowledge, explored and highlighted the link between the data-driven smart solutions and the sustainable development strategies in the context of data-driven

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sustainable smart cities as a new paradigm of urbanism.

Keywords: Data-driven cities, Smart cities, Data-driven sustainable smart cities, Data-driven technologies, Applied solutions, Competences, Infrastructure, Urban systems and domains, Sustainability

Introduction

As predicated by the United Nations, more than half of the world's population live currently in urban areas, and around 70% will be concentrated in the cities by the year 2050. This anticipated urbanization of the world pose significant challenges related to environmental, economic, and social sustainability (e.g., Bibri 2018a, 2019a, 2020a; David 2017; Han et al. 2016; Estevez et al. 2016). Nevertheless, modern cities have a defining role in sustainable development and a central position in applying advanced technologies to support progress towards sustainability in the face of urbanization. In other words, sustainable smart cities, the leading paradigm of urbanism today, are seen as the most important arena for sustainability transitions in an increasingly urbanized world. They hold great potential to instigate major, and make significant contributions to, societal transformations by linking together the agendas of sustainable development and technological innovation.

However, in the current climate of the increased uncertainty and complexity of the world, it may be more challenging for smart cities to reconfigure themselves more sustainably and efficiently. This implies that the city governments in the technologically advanced nations will face significant challenges due to the issues engendered by urban growth. These issues include increased energy consumption, pollution, toxic waste disposal, resource depletion, inefficient management of urban infrastructures, ineffective planning processes and decision–making systems, saturated transport networks, endemic congestion, and social inequality and socio-economic disparity (Bibri and Krogstie 2017a, b). In a nutshell, urban growth raises a variety of problems that jeopardize the sustainability of cities, as it puts an enormous strain on urban systems as well as ecosystem services.

To disentangle these kinds of wicked problems, intractable issues, and special conundrums requires evidently major advancements of urbanism. In this respect, modern cities need to develop and implement more innovative solutions and sophisticated approaches underpinned by cutting–edge technologies and groundbreaking scientific knowledge. This is necessary to monitor, understand, analyze, and plan cities to improve sustainability, efficiency, resilience, equity, and the quality of life. Indeed, a number of alternative solutions based on advanced Information and Communication Technology (ICT) have materialized in recent years and are rapidly evolving, providing the raw material for how smart cities can enhance their performance with respect to sustainability in the face of the expanding urbanization (Bibri 2019b). In this respect, the IoT and big data technologies are seen as a key driver behind the emergence of smart cities (e.g., Ahmed et al. 2017; Batty et al. 2012; Hashem et al. 2016; Rathore et al. 2016, 2018) and sustainable smart cities (Bibri 2019a, 2019c, 2020a). It is estimated that 50 billion devices will be connected to the Internet by 2020 (Perera et al. 2014). Already, the number of objects connected to the Internet (e.g., computers, smartphones, WiFi-enabled sensors, wearable devices, household appliances, and many more) has, according to the Cisco report, exceeded the number of human beings in the world (Ahmed et al. 2017). The continuously increasing number of networked devices deployed across urban environments will in turn result in the explosive growth in the amount of the data generated. Therefore, big data analytics is increasingly seen to provide unsurpassed ways to address a range of rising environmental and socio–economic concerns facing modern cities. The multifaceted potential of ICT has been under investigation by the UN (2015) through their study on 'Big Data and the 2030 Agenda for Sustainable Development.' There is a general consensus that the potential of big data technology for the advancement of sustainability is still largely untapped, and a concerted action is needed to unlock and exploit this potential.

Big data technologies have become essential to the functioning of smart cities (e.g., Batty 2013; Kitchin 2014, 2015, 2016; Townsend 2013), particularly in their endeavor to improve their sustainability performance (Al Nuaimi et al. 2015; Hashem et al. 2016; Batty et al. 2012; Bettencourt 2014; Bibri 2019c, 2020a). Besides, "we are moving into an era where instrumentation, datafication, and computation are routinely pervading the very fabric of modern cities, coupled with the … integration and coordination of their systems and domains. As a result, vast troves of data are generated, analyzed, harnessed, and exploited to control, manage, and regulate urban life" (Bibri 2019b, p. 1).

The wave of the datafication of cities, as mainly enabled by the IoT technology, is giving rise to a new phenomenon–known as the data–driven city. The form of data–driven urbanism has become the key mode of production for both smart cities (Kitchin 2015, 2016) and sustainable smart cities (Bibri 2019a, 2019c). This has resulted from thinking about urbanization and sustainability and their relationships in a data–analytic fashion for the purpose of enhancing and applying knowledge–driven, fact–based, strategic decisions pertaining to various urban systems and domains (Bibri and Krogstie 2018). Unsurprisingly, there has recently been a conscious push for smart cities across the globe to be smarter and thus more sustainable by developing and implementing data–driven solutions to enhance and optimize their operations, functions, services, designs, strategies, and policies in the hopes of achieving the required level of sustainability and improving the living standards of citizens.

While smart cities have played a key role in transforming different areas of human life, they involve deficiencies, inconsistencies, and misunderstandings as to incorporating the objectives of sustainable development in their strategies (e.g., Bibri and Krogstie 2017a; Höjer and Wangel 2015; Kramers et al. 2014; Marsal-Llacuna 2016). Many of the emerging smart solutions are not aligned with sustainability goals in the context of smart cities (Ahvenniemi et al. 2017). There is a weak connection between smart targets and sustainability goals (Bifulco et al. 2016), despite the proven role of advanced ICT, especially big data analytics and its applications, in supporting smart cities in moving towards sustainability (e.g., Al Nuaimi et al. 2015; Angelidou et al. 2017; Batty et al. 2012; Bibri 2018a, 2020a; Bettencourt 2014). In fact, while the research on big data and the IoT technologies has recently been active in the area of smart cities, the bulk of work tends to deal largely with economic growth, service efficiency, and governance (e.g., Ahmed et al. 2017; Kitchin 2014, 2015, 2016; Hashem et al. 2016; Rathore et al. 2018). This area of research overlooks or barely explores the untapped potential of data-driven solutions for advancing sustainability. These gaps have been identified as part of a thorough literature review conducted by Bibri (2019c). And this study attempts to explore them by investigating the role of big data technologies and their applications in advancing smart cities in terms of sustainability from a practical perspective under what is labelled "data-driven sustainable smart cities."

This paper investigates how the emerging data-driven smart city is being practiced and justified in terms of the development and implementation of its innovative applied solutions for sustainability. As with all approaches to smart urbanism, data-driven cities have commonalities and differences depending on the challenges they face and thus the innovative solutions they prioritize. While all smart cities are set to face the same challenges of sustainability in the face of the escalating scale and rate of urbanization, they tend to differ in terms of the strategies they pursue to overcome them. City governments do not have a unified agenda of sustainable development, and data-driven decisions are unique to each city. While big data are seen as the answer, each city sets its own questions and determines the ways to address them. The motivation for this study is to identify the core dimensions of the emerging data-driven smart city and to use the outcome to inform the backcasting study that is being conducted to analyze, investigate, and develop a novel model for data-driven smart sustainable cities of the future in terms of its technological components.

The remainder of this paper is structured as follows. Section 2 provides the key conceptual and theoretical constructs that make up this study. Section 3 details and justifies the research methodology adopted in this study. Section 4 provides an overview of the literature review previously conducted in relation to this study. Section 5 presents the results, which are, in Section 6, discussed and interpreted in perspective of previous studies. Finally, this paper concludes, in Section 7, by drawing the main findings, providing some reflections, and suggesting some avenues for future research.

Conceptual and theoretical background

The data–Driven City as an emerging paradigm of smart urbanism

The data-driven city is one of the recent faces and future forms of smart cities. As such, it represents an emerging paradigm of smart urbanism. Indeed, it is too often associated with 'smarterness' under what is labeled 'data-driven smart cities', since big data technology is seen as an advanced area of ICT, which is an enabler of all approaches to smart cities (e.g., ambient city, sentient city, ubiquitous city, real-time city, etc.) as an umbrella term. There is no definite definition or a single conceptual unit of a data-driven city, nor is there an agreed industry description thereof. Therefore, multiple definitions have been suggested, with each tending to offer a particular view of the concept based on the context of big data uses and applications, thereby serving as a constituting or complementary aspect of a rather still evolving concept.

Broadly, the phenomenon of the data-driven city has materialized as a result of the emergence of big data science and analytics and the adoption of the underlying technologies in scholarly research and social practice, the explosive growth of urban data, and the transformation of urban landscape in the light of urbanization. These developments can be used in a range of proposals for a conceptual framework for a data-driven city. As an example, Nikitin et al. (2016) use, in their research framework, a notion which embraces the basic elements used in the management of the data-driven city: data, processing technologies, and government agencies. The authors accordingly describe the data-driven city as a city that is characterized by the ability of agencies of city management to use technologies for handling the data for the adoption of solutions for enhancing living standards thanks to the development of social, economic and ecological areas of urban environment.

One of the key foci of the data-driven city is sustainable development. In this respect, Bibri (2020a) describes a data–driven smart sustainable city as a city that is increasingly composed of and monitored by ICT of ubiquitous computing and thus has the ability of using advanced technologies and solutions (i.e., horizontal information systems, operations centers, service agencies, research centers, innovation and living labs, and strategic planning and policy offices) for generating, storing, processing, analyzing, and harnessing urban data for enhanced decision-making and deep insights pertaining to sustainability, efficiency, resilience, and the quality of life.

Datafication

The data-driven city is a city that implements datafication for enhancing and optimizing its operations, functions, services, strategies, and policies. Broadly, datafication refers to the collective tools, processes, methods, techniques, and technologies used to transform a city to a data–driven enterprise. The intensification of datafication is manifested in the radical expansion in the volume, range, variety, and granularity of the data generated about urban environments and citizens (Bibri 2019b, 2020a; Crawford and Schultz 2014; Kitchin 2014, 2016; Strandberg 2014), with the aim to quantify the different aspects of urbanity in the modern city.

Cities today are dependent upon their data to operate properly—and even to function at all with regard to many domains of urban life. A city that implements datafication is said to be datafied. To datafy a city is to put it in a quantified format so that it can be structured, harnessed, and analyzed. Cities are currently taking any possible quantifiable metric and squeezing value out of it by enhancing decision–making pertaining to a wide variety of practical uses in relation to many urban systems and domains. In a modern data–oriented urban landscape, a city's performance is measured, assessed, and enhanced based on the ability of having control over the storage, management, processing, and analysis of the urban data, as well as on the knowledge extracted from these data in the form of applied urban intelligence. Tackling the challenges of sustainability and mitigating the negative effects of urbanization are among the key concerns of the datafication of the modern city (Bibri 2019a, 2020a).

The internet of things (IoT)

The IoT has become a key component of the ICT infrastructure of smart cities due to its great potential to advance sustainability. According to Giusto et al. (2010), the IoT is a "communication paradigm which visualizes a near future, in which physical objects are equipped with micro–controllers, transceivers for digital communication and fitting protocol stacks that will make these objects able to communicate with each other and with the users." Bibri (2020a) defines the IoT as the interconnection of uniquely identifiable embedded devices and smart objects connected to humans, embedded in their environments, and spread along the trajectories they follow using the Internet Protocol version 6 (IPv6), embedded systems, intelligent entities, and communication and sensing–actuation capabilities. The IoT is evolving into more and more sophisticated network of sensors and physical objects involving all kinds of everyday objects, including individuals, roads, railways, bridges, street lighting, buildings, water systems, energy systems, distribution networks, vehicles, appliances, machines, and air. In short, the connectivity achieved by the IoT encompasses people, machines, tools, and places. Reports show that the number of Internet–connected devices is expected to increase more than twofold from 22.9 billion in 2016 to 50 billion by 2020 (Ahmed et al. 2017).

As one of the prevalent ICT visions of pervasive computing, the IoT is associated with big data analytics. A great part of the unfolding deluge of urban data is due to the IoT as a form of ubiquitous computing. To gain further insights into this relationship, the interested reader might want to read a recent survey carried out by Qin et al.'s (2016) and Bibri (2018b). However, the IoT entails complex sensor infrastructure and network, and thus requires novel techniques, tools, processes, and models to handle the volume, variety, and velocity of the data generated to enable new services and applications.

The IoT is viewed as part of the Internet of the future, which is expected to be dramatically different from what has hitherto been experienced in terms of the use of the Internet as we know today. The use of the IoT is intended to achieve different intelligent functions from information exchange and communication, including learning about things, identifying things, tracking and tracing things, connecting with things, searching for things, monitoring things, controlling things, evaluating things, managing things, operating things, repairing things, and planning things. In short, the objective of the IoT is to enable communications with and among smart objects as well as with people and their environment, without any human intervention. Zanella et al. (2014) state that "the intention of the IoT is to make the Internet even more engaging and omnipresent by allowing easy entrance and communication with a large variety of devices so that it can support the development of a number of applications which make use of the possibly gigantic bulk and diversity of the data produced by objects to present new services to citizens, companies and public administrations." This involves the value that is to be extracted from the deluge of urban data for enhanced decision–making and deep insights associated with a wide variety of practical uses and applications in relation to sustainability. This is associated with smart cities (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Hashem et al. 2016), data-driven cities (Nikitin et al. 2016), and sustainable smart cities (Bibri 2019c, 2020a). The IoT–based infrastructures will allow different classes of cities to devise solutions for solving different problems in a more efficient, effective, and responsible way. The upcoming data avalanche is the primary fuel of this new age where powerful computational processes use this fuel to create more sustainable, efficient, resilient, livable, and equitable cities.

Sustainable smart urbanism: a data-driven approach to sustainable urban development

Rooted in the study of the relationship between urban planning and sustainable development in a rapidly urbanizing world, sustainable urbanism is concerned with the study of cities and the practices to build them that focus on promoting their long term resilience and viability by reducing material use, lowering energy consumption, mitigating pollution, and minimizing waste, as well as improving social equity, the quality of life, and well-being.

The sustainable smart city as a holistic paradigm of urbanism represents an approach to sustainable urban development, a strategic process to achieve the long–term goals of urban sustainability—with support of advanced technologies and their novel applications. Accordingly, achieving the status of such city epitomizes an instance of urban sustainability. This notion refers to a desired (normative) state in which a city strives to retain a balance of the socio–ecological systems through adopting and executing sustainable development strategies as a desired (normative) trajectory. This balance entails improving and advancing the environmental, economic, social, and physical systems of the city in line with the vision of sustainability over the long run—given their interdependence, synergy, and equal importance. This strategic goal requires fostering linkages between scientific research, technological innovations, institutional frameworks, policy formulations, planning practices, and development strategies in relevance to sustainability.

Furthermore, the sustainable smart city relies on constellations of instruments across many scales that are connected through multiple networks augmented with intelligence, which provide and coordinate continuous data regarding the different aspects of urbanity in terms of the flow of decisions about the environmental, economic, social, and physical forms of the city. The evolving research and practice in the field of sustainable smart urbanism tends to focus on harnessing and exploiting the ever–increasing deluge of the data that flood from urban systems and domains by leveraging the value extracted from this deluge through analytics in advancing sustainability. In this respect, sustainable smart urbanism entails developing urban intelligence functions as an advanced form of decision support, which represent new conceptions of how the sustainable smart city functions and utilizes and integrates complexity science, urban science, and data science in fashioning powerful new forms of urban simulations models and optimization and prediction methods. These can generate urban structures and forms that improve sustainability, efficiency, resilience, and the quality of life.

The data–driven solutions are of paramount importance to sustainable smart urbanism as a set of processes and practices. One key aspeect of this is the use of urban data as the evidence base for formulating urban policies, plans, strategies, and programs, as well as for tracking their effectiveness and modelling and simulating future urban development projects. In addition, the operation and organization of urban systems and the coordination of urban domains require not only the use of complex interdisciplinary knowledge, but also the application of sophisticated approaches and powerful computational analytics (e.g., Batty et al. 2012; Bibri 2019a, 2020a; Bibri and Krogstie 2017b, Bibri and Krogstie 2018; Bibri et al. 2020a; Bettencourt 2014). In their comprehensive survey on emerging data–driven smart cities, Nikitin et al. (2016) point out that modern cities employ the latest technologies in city management to support sustainable development given rapid urban growth, increasing urban domains, and more complex infrastructure.

Literature review

This study is based on a thorough literature review conducted by Bibri (2019c)—an article entitled “On the Sustainability of Smart and Smarter Cities in the Era of Big Data:

An Interdisciplinary and Transdisciplinary Literature Review." This literature review provides a theoretical foundation for this study in terms of what is already known, produces a rationale for this study as to its contribution of something new to the body of knowledge, helps understand where excess research exists and what kind of questions are left unanswered, substantiates the presence of research problem in regard to what is needed to be known, and frames research methodology, approach, and aim. In a nutshell, what is accomplished by this literature review is knowing the current status of the body of knowledge in the research field of smart urbanism, which is an essential first step for this study. The main aspect of this status pertains to the gaps identified and how to explore them by investigating the role of big data technologies and their applications in advancing smart cities in terms of sustainability from a practical perspective under what is labelled "data-driven sustainable smart cities".

To find out about what is known about the topic on focus, Bibri (2019c) provides a comprehensive, state–of–the–art review on the sustainability and unsustainability of smart cities in relation to big data technology, analytics, and application in terms of the underlying foundations and assumptions, research problems and debates, opportunities and benefits, technological developments, emerging trends, future practices, and challenges and open issues. An exhaustive, by its nature, a methodological approach is adopted for carrying out this interdisciplinary literature review, thereby delivering a relatively complete census of the relevant existing work on the topic. Such approach entails search strategy and scholarly sources, inclusion and exclusion criteria, purposes, and organisational approaches. As regards the findings, this study reveals that tremendous opportunities are available for utilizing big data technologies and their applications in smart cities of the future. This is to enhance and optimize urban operations, functions, services, designs, strategies, and policies in line with the goals of sustainability, as well as to find answers to challenging analytical questions and to transform the knowledge of smart urbanism. However, just as there are immense opportunities ahead to embrace and exploit, there are enormous challenges and open issues ahead to address and overcome in order to achieve a successful implementation of big data technologies and their applications in smart cities of the future. These findings serve to aid strategic city stakeholders in understanding what they can do more to advance sustainability based on data-driven technological solutions under what is labeled 'data–driven sustainable smart cities,' and to give policymakers an opportunity to identify areas for further improvement while leveraging areas of strength with regard to the emerging and future form of urbanism.

Case study methodology

Case study as an integral part of a Backcasting-based futures study

This case study is an integral part of an extensive futures study that is being conducted to analyze, investigate, and develop a novel model for data-driven smart sustainable cities of the future using backcasting as a scholarly and planning approach (Bibri and Krogstie 2019a, 2019b). Specifically, it is associated with the empirical phase of the backcasting-based futures study. The term "backcasting" was coined by Robinson (1982), and the approach was originally developed in the 1970s as an alternative to traditional energy planning and employed as a novel analytical tool for energy planning using normative scenarios. Backcasting scenarios are used to explore future uncertainties encountered in society, create opportunities, build capabilities to take strategic steps, guide policy actions, and enhance decision–making processes (Bibri and Krogstie 2019a, 2019b). They allow for new options to be considered reasonable, thereby widening the perception of what could be feasible and realistic in the long-term (e.g., Dreborg 1996; Höjer and Mattsson 2000). The fundamental question of backcasting-based futures studies is: "If we want to attain a certain goal, what strategic actions must be taken to get there?" Accordingly, backcasting starts with defining a desirable future and then works backwards to identify the strategic steps needed to build feasible and logical pathways between states of the future and the present. Developing pathways from this perspective allows to imagine the impacts of alternative scenarios, which are commonly used as a tool for strategic planning, especially in relation to sustainability. Having a strongly normative nature, backcasting is especially well equipped to be applied to sustainability issues (Bibri 2018c; Dreborg 1996; Holmberg 1998; Quist 2007; Robert et al. 2002). Many authors have justified the need for a normative scenario approach by referring to the emerging disruptions in societal development (Dreborg 1996; Quist and Vergragt 2006), e.g., technological breakthroughs, data-intensive scientific discovery, and sustainable development.

Case study Research

Case study research has long been of prominence in many disciplinary and interdisciplinary fields. As a research methodology, case study is well established in different scientific and technological fields. Creswell et al. (2007, p. 245) describe case study methodology as "a type of design in qualitative research, an object of study, and a product of the inquiry." The authors conclude with a definition that collates the hallmarks of key approaches and that represents the core features of a case study: "a qualitative approach in which the investigator explores a bounded system (a case) or multiple bounded systems (cases) over time through detailed, in–depth data collection involving multiple sources of information and reports a case description and case–based themes" (Creswell et al. 2007, p. 245).

Case study design category

According to their design, case studies can be divided into several categories, including descriptive, explanatory, exploratory, illustrative, cumulative, and critical instance, each of which is custom selected for use depending on the objectives of the researcher or the purpose in evaluation. Case study research can be used to study a range of topics using different approaches for different purposes (Simons 2009; Stake 2006; Stewart 2014; Yin 2017). With that in mind, this case study uses a descriptive design, an approach which is focused and detailed, and in which questions and propositions about the phenomenon of the data-driven smart city are scrutinized and articulated at the outset. The articulation of what is already known about this phenomenon is referred to as a descriptive theory, which in this context pertains to smart urbanism. Therefore, the main goal of this descriptive case study is to assess the selected cases in detail and in depth based on that articulation. This research design intends to describe the phenomenon in question in its real–world context, to draw on Yin (2014, 2017). It is worth pointing out that the internal validty in this research design, the approximate truth about inferences regarding cause-effect in relation to this phenomenon is not relevant as in most descriptive studies. It is rather relevant in studies that attempt to establish a causal relationship such as explanatory case studies. Indeed, descriptive research is used to describe some characterisitics of certain phenomena, and does not address questions about why and when these characteristics occur - no causal relationship.

Descriptive case study relevance and approach

Descriptive research here involves the description, analysis, and interpretation of the present nature, composition, and processes of data-driven smart cities, where the focus is on the prevailing conditions, or how these cities behave in terms of what has been realized and the ongoing implementation of plans based on the corresponding practices, strategies, and solutions. Moreover, as an urban event based on two instances, the data-driven smart city involves a set of indicators of an integrated city system in operation that requires an analysis to allow obtaining a broad and detailed form of knowledge about such system. To achieve this, we adopted an approach that consists of the following steps:

- Using a narrative framework that focuses on the data-driven smart city as a real–world problem and provides essential facts about it, including relevant background information
- Introducing the reader to key concepts, technologies, practices, and strategies relevant to the problem under investigation.
- Explaining the actual solutions in terms of plans, the processes of implementing them, and the expected outcomes.
- Offering analysis and evaluation of the chosen solutions and related issues, including strengths, weaknesses, tradeoffs, and lessons learned.

One of the essential requisites for employing case study stems from one's motivation to illuminate a complex phenomenon (Merriam 2009; Stake 2006; Yin 2017). Accordingly, the outcome of this descriptive case study should serve as an input to Step 5 (specifying and merging the components of the socio–technical system to be developed) and Step 6 (performing backcasting backward–looking analysis) of the backcasting study, By carefully studying any unit of a certain universe, we are in terms of knowing some general aspects of it, at least a perspective that guides and informs subsequent research (Wieviorka 1992). In other words, descriptive case studies often represent the first scholarly toe in the water in new areas of inquiry.

Descriptive case study as a basis of Backcasting

One important use of the case study approach in research is planning, which in turn is at the core of the backcasting approach to futures studies. However, the purpose of analyzing and evaluating the two cases considered here together with the other four cases—two compact cities (Bibri et al. 2020b) and two eco–cities (Bibri and Krogstie 2020)—is to provide a foundation for backcasting the future phenomenon of the data-driven smart sustainable city. In this case, it is necessary first and foremost to define which characteristics of the future state of this phenomenon are 'interesting' and should be included in the backcasting (see Bibri and Krogstie 2019a, 2019b for Step 1, 2, and 3 of the backcasting study). Evidently, recent data in this regard are of primary importance as a basis for the backcasting. Other material needed to make a backcasting depends on how strong a 'theoretical and disciplinary framework' we have about the expected data-driven smart sustainable city of the future and its internal relationships (see Bibri 2018a, 2019a, 2020a for further details). Commonly, quite a strong basis for backcasting is available when there is such a framework which underpins and explains the phenomenon in question in terms of its foundation and justification, as well as its associated outcomes as a new and future paradigm of urbanism. All in all, the results of all the case studies carried out are intended to guide and inform the backcasting study in question as an overarching scholarly endeavor.

Selection criteria, unit of analysis, and data collection and analysis methods

The selection of all of the cases studied was done in line with the overall aim of the futures study being carried out. The primary purpose of investigating the cases of Barcelona and London is to identify the set of the data-driven solutions that are needed to develop the proposed model for data-driven smart sustainable cities of the future in terms of its technological components. The urban components of this model have already been identified through two separate case studies: compact city strategies and eco-city strategies, as mentioned earlier.

Selecting Barcelona and London amongst all the top cities leading the 'smart city' ranking (e.g., Eden Strategy Institute 2018) and the 'data-driven' city ranking (Nikitin et al. 2016) in the world is justified by three key reasons. First, the focus of the backcasting study, and thus this paper, is on the European Cities of which London and Barcelona are the leading data-driven smart cities. Second, both cities are widely recognized and mostly reputed for using data-driven technology solutions in their operational functioning, management, and planning, and what this entails in terms of competences, infrastructure, and data sources (e.g., Bibri 2020a; Batty 2013; Eden Strategy Institute 2018; Kitchin 2014, 2016; Nikitin et al. 2016; Sinaeepourfard et al. 2016). Third, they are increasingly seen as the leading European cities that are taking the initiative to use and apply big data technology to advance sustainability—thereby evolving into data-driven sustainable smart cities (Bibri 2020a). The local governments of London and Barcelona have established a number of projects and implemented several planning measures for modernizing their ICT infrastructure and strengthening their readiness to integrate data-driven solutions and approaches into urban processes and practices.

In view of the above, the two cities demonstrate exemplary practical initiatives as regards the integration of data-driven solutions and sustainable development strategies. As such, they may be seen as successful examples of the emerging paradigm of smart urbanism, as well as critical cases in sustainable development within the technologically advanced nations. All in all, the selection criteria secured cases where advancements in big data technologies and their novel applications for sustainability, coupled with future visions in this regard, are present. This in turn is at the core of the backcasting study in respect of the integrated model under development.

The focus of the backcasting study constitutes the basis for determining the unit of analysis concerning the cases in question. The object of study in this paper, the entity that frames what is being analyzed, is the applied solutions of the emerging data-driven smart cities and to what extent they contribute to and produce the benefits of sustainability. This is essential to focalizing, framing, and managing data collection and analysis.

To identify and analyze the relevant dimensions of the data-driven smart city with respect to sustainability, a thematic analysis approach was designed and employed. Thematic analysis is particularly (albeit not exclusively) associated with the analysis of textual material (in this context, plans, programs, project descriptions, policy documents, and secondary data sources). Generally, it emphasizes identifying, analyzing, interpreting, and reporting themes, i.e., important patterns of meaning within qualitative data that can be used to address the problem under investigation. Braun and Clarke (2006) suggest that thematic analysis is flexible in terms of theoretical and research design given that it is not dependent on any particular theory or epistemology: multiple theories can be applied to this process across a variety of epistemologies.

Thematic analysis is an umbrella term for a variety of different approaches, which are divergent in regard to procedures. We adopted an inductive approach to thematic analysis, which allows the data to determine the set of themes that are to be identified in line with the aim of this study. That is to say, we developed our own framework based on what we find as themes (inductive) by discovering patterns, themes, and concepts in the data collected.

The main steps of the analytical approach are as follows:

1. Review of city data (i.e., plans, programs, project descriptions, policy documents, and other secondary data sources) and the scientific literature that is related to the role of data-driven technologies in advancing sustainability. The outcomes of this process are numerous themes that are associated with the emerging data-driven approach to smart urbanism. It is important to have a comprehensive understanding of the content of the documents and scientific literature and to be familiarised with all aspects of the data. This step provides the foundation for the subsequent analysis.
2. Pattern recognition (searching for themes) entails the ability to see patterns in seemingly random information. The aim is to note major patterns within the result of the first step. This second step looks for similarities within the sample and codes the results by concepts and themes. Coding involves identifying passages of text that are linked by a common theme, allowing to index the text into categories and thus establish a framework of thematic ideas about it. In this step, the preliminary codes identified are the features of the data that appear interesting and meaningful, and the relevant data extracts are sorted according to overarching themes. It is important to allude to the relationship between codes and themes.
3. Reviewing themes is about combining, separating, refining, or discarding initial themes in line with the aim of this study and thus the backcasting study. Data within themes should cohere together meaningfully and be clear and identifiable in terms of the distinction between them. A thematic 'map' is generated from this step.

4. Producing the report involves transforming the analysis into an interpretable piece of writing by using vivid and compelling data extracts that relate to the themes, research aim, and literature associated with this study. The report must go beyond a mere description of the themes and portray an analysis supported with empirical evidence that addresses the research problem.

All in all, the descriptive case study approach was applied here as a framework to collect and analyze data from different documents related to the selected cases. A thematic analytical approach was employed to deal with the "case-based themes" (Creswell et al. 2007). The backcasting methodology is adopted in the overarching futures study to combine the results of this case study with those of the other aforementioned case studies in order to develop a new paradigm of urbanism.

Results

On the ranking and score of London and Barcelona

Technologies and readiness

In the early 2010s, London and Barcelona were the first European cities to implement data-driven smart technologies to improve their services. They invested heavily in their ICT infrastructure, including an extensive IoT sensor network collecting data about transport, energy, environment, security, healthcare, and so on. Implemented in London and Barcelona is a broad range of applied technological solutions based on the analysis of the data generated by a variety of sources, with the aim to improve the quality of life of citizens. The focus of the Smart London Plan is on using the creative power of big data technologies to serve citizens and improve their lives (London City 2018). In 2015, Barcelona took the initiative of the smart city in a new direction by setting a goal of democratizing its ICT infrastructure, with a vision to develop it by and for the people (Bibri 2020a). That is, to serve people as technology users—instead of a technology push agenda.

In their comparative study of the practice of urban data-based management using statistical analysis and expert analysis, Nikitin et al. (2016) analyze the data-based technologies applied in the 28 megalopolises of the world to compare cities by the number of references in a variety of types of sources, and identify London and Barcelona among the first four leading cities. The results of this analysis are illustrated in Fig. 1.

Table 1 briefly describes the key indicators associated with the comparative analysis of the two cities in relevance to this study, namely readiness and technologies. These indicators are the key foci of this study.

Smart City government score

In ranking the top 50 smart city governments in the world, Eden Strategy Institute (2018) classifies the governments of London and Barcelona as the leading in Europe, and calculates a total score for each based on different aspects related to the smart city initiative (Fig. 2).

Data-driven technologies and their applications for City systems and domains

Smart cities are increasingly embracing big data technologies and their novel applications, especially those related to and enabled by the IoT. This is due to the tremendous, yet

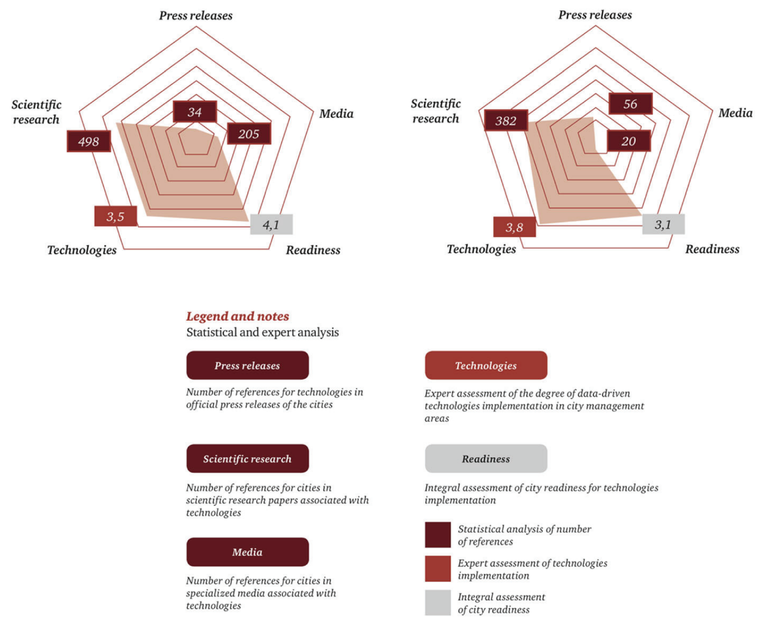


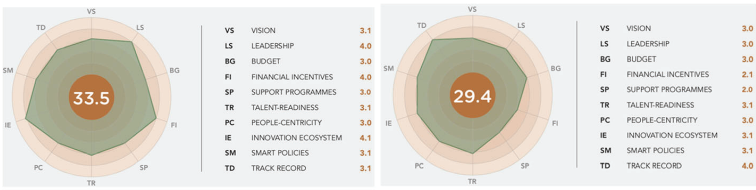
Fig. 1 A comparative analysis of London and Barcelona

untapped, potential of big data analytics for adding a whole new dimension to sustainability in an increasingly urbanized world. There is a huge range of data-driven applications that are compatible with the goals of sustainable development. As with all the emerging smart cities focusing on sustainability, London and Barcelona may differ on the level of the development of data-driven technologies and that of their implementation in city systems and domains. One of the recent studies that have addressed these issues and aspects with respect to these cities is the one conducted by Nikitin et al. (2016). The results reported in this regard are presented in Table 2.

While the two cities have a high level of the development of data-driven technologies, they slightly differ in the level of the implementation of these technologies in different urban systems and domains. This indicates differences in the agenda of city development, including in relation to sustainability. The effectiveness of individual initiatives as related to different domains (e.g., transport, traffic lights, energy, environment, etc.) may also vary significantly between London and Barcelona with respect to the extent to

Table 1 Indicators of data-driven technology implementation and its readiness

Cities	Indicators of data-driven implementation of technologies and its readiness
London	The municipal systems are highly ready for the introduction of technologies. London stands apart with a decentralised development model. The agenda shows the impact of creative industries on settlement patterns, distribution of activities within the city and geographical location-related services.
Barcelona	Barcelona stands out with its high level of technology development and is highly ready to further implementation. Barcelona is extensively implementing data-based solutions. "Modelling", "efficiency" and "optimisation" are used in the texts.



(a) (b)

Fig. 2 Smart City Government Score of London (**a**) and Barcelona (**b**). Source: Eden Strategy Institute (2018)

which the planned objectives can be achieved. Regardless, scholars agree on the high value of the implementation of data-based decisions in smart urbanism with respect to sustainability (e.g., Al Nuaimi et al. 2015; Batty et al. 2012; Bettencourt 2014; Bibri 2018a, b, 2019a, 2019b, c).

London and Barcelona are among the world leaders in the implementation of the data-based technologies and decisions (Nikitin et al. 2016). London is one of the leaders in advanced technologies and digitization (Pozdniakova 2018). Both cities have the highest level of technology adoption in Europe as observed in various systems and domains, with a slight difference in a few of them. The greatest variety of the data-based decisions is found in the systems and domains of transport and security in both cities (Nikitin et al. 2016). The extensive use of such decisions (e.g., traffic control, public transport planning, etc.) is based on the IoT (e.g., geolocation and Radio Frequency Identification (RFID) and Near Field Communication (NFC) technologies), which allows to automate or support a variety of decisions.

Transport, traffic, and mobility

Transport and traffic management is generally the most popular area of using data-driven solutions within smart cities and sustainable smart cities (e.g., Aguilera et al. 2013; Batty 2013; Bibri 2018b, 2019b; Hashem et al. 2016; Shang et al. 2014). Both London and Barcelona apply the data-driven technology for transport and traffic management. With respect to London, the application of such technology pertains to the management of transport services on the basis of the data received by the situation center, as well as the automatic control of traffic signals on the basis of the data collected on traffic congestion using sensors embedded in the traffic lights. As regards Barcelona, the application entails monitoring the movements of public transport by means of Global Positioning System (GPS) sensors, as well as the smart traffic light system for the automatic provision of priority to public transport and other types of transport such as emergency services. Further development in the domain of transport technology in London and Barcelona is going in the direction of the automation of management in real time (i.e., smart traffic lights, smart parking, automatic traffic alerts, etc.). Implemented in Barcelona is several technological innovations that improve city operations

Table 2 Assessment degree of technology implementation based on a scale between 2.5 and 5.0

	Technology implementation	Transport	Utilities	Safety	Environment	Healthcare	Others
London	3.5	4.0	3.5	3.0	3.0	3.0	4.5
Barcelona	3.8	4.0	4.5	3.0	5.0	3.0	3.5

in regard to transport. Among the solutions applied in this regard are (Bibri 2020a; Ilhan and Fietkiewicz 2017; Eden Strategy Institute 2018):

Orthogonal bus system: the city's bus network is based on an orthogonal grid scheme, which promotes intermodality, strategically placing bus stops to allow connection between bus lines as well as trams, metro trains, bicycles, etc. Because buses are laid out on a grid, every bus line intersects with multiple other bus lines, so citizens can reach any point in the city without changing buses more than once. Hybrid buses are used to decrease emissions, and solar-powered signs show times of arrival at bus stops. The bus network is based on data analysis of the most common traffic flows in Barcelona, utilizing primarily vertical, horizontal and diagonal routes with a number of interchanges. Integration of multiple smart technologies can be seen through the implementation of smart traffic lights as buses run on routes designed to optimize the number of green lights.

Bicing—a bicycle sharing system: the system offers 6000 bicycles which can be borrowed for short trips across the city. Bicycle pickup stations are placed near public transportation and parking areas, making it convenient for citizens to pick up or drop off bicycles. Citizens pay an annual fee and check for bicycle availability using the Bicing app, which has more than 120,000 users.

Smart parking system: This solution enables to reduce traffic by helping drivers find parking places, decreases congestion, and makes the streets safer. Wireless sensors are implemented underneath the roads and installed on the streets to guide vehicle drivers to available parking spots, enabling real-time query via a smartphone app. This app also enables paying for parking and provides parking data for use by other smart city systems. The smart parking system had operational challenges because the original magnetic sensors were set off by passing trains and falsely reported parking slots as occupied, and as a result, the project was deprioritized.

In addition, Barcelona uses smart traffic lights for optimizing the traffic in the real time mode. A smart system manages the traffic lights by processing the information received from the traffic magnetometer sensors with wireless capabilities This eliminates disruptions to the traffic flow, among others.

Street lighting is being expanded beyond its original use, e.g., illuminating the streets, making citizens feel safer, monitoring energy consumption, saving costs, and so on. It has been argued that street lights and city-wide lighting infrastructure could be the backbone for building sustainable smart cities of the future by transforming urban spaces in such a way that they can collect data that can make urban living more environmentally sustainable and enhance citizens' lives thanks to the IoT and related sensor networking and communication capabilities. In this regard, the lighting infrastructure could facilitate and incorporate a number of applications related to traffic, mobility, pollution, air quality, parking, public Wi-Fi connectivity, and so forth. Speaking at the Smart To Future Cities conference in London, Ms. Kressler said: "Street lighting is an ideal backbone, and the most interesting pathway, to employing the IoT technologies in cities. Technology is just an enabler–a smart city will only be successful if it shows real benefits to its citizens and its civic leaders" Forsdick (2019a). She moreover states that 40% of the local authority's energy budget is spent on street lighting, while smart street light controls and the IoT connectivity can create energy savings of 70% to 80%. What makes the lighting infrastructure an effective applied technological solution for sustainability is its pervasiveness, connection to power supply system, and high visual impact. As such, it enables smart cities to achieve their sustainability ambitions at a lower cost, particularly in connection with environmental sustainability.

With respect to Barcelona, smart lighting entails sensor-controlled light emitting diode (LED) lights for pedestrian and bicycle paths, self-controlled-LED street lights with preset lighting schedules, and remote-controlled lights. Accordingly, the street lights are powered by energy-efficient LED technology and use sensors to detect when lights are required (e.g., turned on when bystanders are present), saving energy and reducing the heat generated by the old lamps. Moreover, they include sensors that detect changes in temperature and pollution levels and are used as Wi-Fi transmitters. This implies that more advanced applications are being integrated into the lighting infrastructure. One of these applications is where an emergency is reported in Barcelona, the approximate route of the emergency vehicle is entered into the traffic light system, setting all the lights to green as the vehicle approaches through a mix of GPS and traffic management software, allowing emergency services to reach the incident without delay. Much of these data is managed by the Sentilo Platform (Bibri 2020a). On the whole, the benefits of the smart lighting solution in Barcelona lie in optimizing the efficiency of the public-lighting installations as well as increasing the level of the security of the streets through quality lighting thanks to the combination of LED lighting and control systems, including light on demand systems and street lighting remote management system.

In addition, according to the Smart London Plan, the city plans to demonstrate how technology can reduce traffic collision and trial new technologies that can reduce the risk of collisions with cyclists and other vulnerable road users (London City 2018). Moreover, at the Smart to Future Cities Conference in London, which was held in April 2019, Smart London Strategy Officer Dr. Stephen Lorimer claims: "Londoners are the first to see the economic, social, and environmental sustainability policies introduced under the same banner through the congestion charge and Ultra Low Emission Zone (ULEZ), and it is the first time residents have tangibly seen that cars are having an impact across all three pillars of sustainability in cities" (Forsdick 2019a).

In terms of urban mobility, a variety of apps are being used by the residents of London and Barcelona to remain updated and connected and to utilize transport and traffic services. Government announces funding for a world-leading Smart Mobility Living Lab in London (TRL 2017). Transport for London (TfL) analyzes the data collected from Oyster cards on public transport events corresponding to entries, exits, transfers, and so on to examine journey patterns. TfL has very detailed data on buses and trains that give precise geo-positioning, times, and delays with respect to timetables, and that can be minded and visualized. A number of algorithms have, since the early 2010s, been developed for constructing multimodal trips associated with the data collected on public transport events. The unified TfL API brings together data across all the modes of transport into a single RESTful API, and provides access to the most highly requested real-time and status information across these modes in a single and consistent way (Nikitin et al. 2016).

In order to mine human mobility data, a number of various analytical methods for spatio-temporal data have been developed to create a variety of mobility apps. Among the mobility apps that are used in Barcelona are (Bibri 2020a):

- TMB virtual: an app that uses mobile phone cameras to navigate citizens to the most relevant public transport stations
- Trànsit: a navigation app updated with real-time traffic conditions for drivers
- fassisApparkB: an app that helps direct drivers to an available parking spot

In London and Barcelona, the data are open and used by app developers as a unique source of real-time data on all the modes of transport for different practical purposes. Big data technologies are able to improve mobility on many levels, thereby increasing spatial and aspatial accessibilities to diverse opportunities. This enables the citizenry to improve the quality of their life. Big data sets concerning human mobility have become the fundamental ingredient for the new wave of urban analytics thanks to the widespread diffusion of wireless technologies, which allow for sensing and collecting massive repositories of spatio-temporal data. This research wave has increasingly attracted scientists from diverse disciplines given its importance in such domains as urban planning, transport planning, public health, economic forecasting, and sustainable mobility. With respect to the latter, for example, the sensors installed in bicycle lanes/cycle tracks and sidewalks/footpaths are able to monitor the number of cyclists and pedestrians to determine the most popular places in the city. Based on this information, the city government can identify priority areas for reconstruction/redevelopment and plan new or alternative routes for cyclists and pedestrians.

Urban infrastructure

Urban infrastructure management constitutes one of the key applications of the IoT and big data analytics in terms of monitoring, control, automation, and optimization. This involves the operations of roads, railway tracks, bridges, and tunnels (e.g., Gubbi et al. 2013). This relates to the events and changes associated with the structural conditions of urban infrastructure that can increase risk and cost and compromise safety and service quality. In this regard, the IoT devices can be used to improve incident management, enhance emergency response coordination and service quality, and reduce operational costs in all infrastructure related areas (Bibri 2018b).

As to the intelligent management of urban infrastructure and distributed network, such as water supply system, power supply system, waste management system, and lighting, a number of data-driven solutions are implemented in London and Barcelona due to the high importance of natural resources in regard to urban development strategies. As stated in the Smart London Plan (2018), the city aims to:

- Promote the use of smart grid technologies to better manage demand and supply of energy and water.
- Stimulate the use of data and technology to bring efficiencies and scale to the separation and utilization of waste as a resource.
- Investigate longer term infrastructure needs up to 2050—and using data and digital technology to meet those needs.

London strongly supports smarter heating, electricity, waste, and water networks that use resources efficiently and do more with less investments. Currently, the main areas of

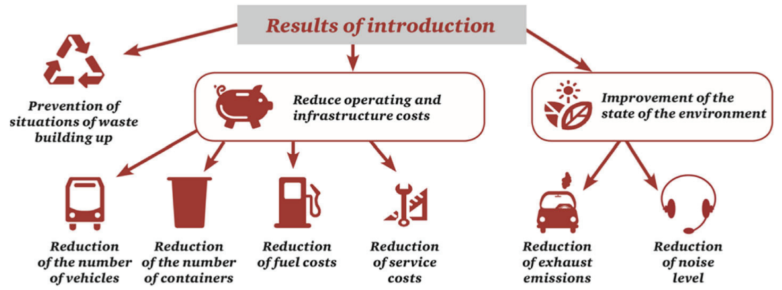


Fig. 3 Smart waste disposal system and its advatages in Barcelona. Source: Nikitin et al. (2016)

data measurement include the London Energy and Greenhouse Gas Inventory (energy consumption by homes, workplace, and transport) and the London Atmospheric Emissions Inventory (air pollution) (Pozdniakova 2018). Renewable energy systems are among the key smart solutions adopted by the City of Barcelona as to using sustainable energy sources to support its power grid system, such as solar panels distributed throughout the city. Considered to be the first regulations of their kind to be enacted in Europe, Barcelona has required the use of solar water heaters by households since 2006 as well as new large buildings to produce their own domestic hot water since 2000 (Bibri 2020a).

Smart waste disposal system, smart grid system, and smart energy management

Public services in London are in the area of responsibility of private companies, and consequently, the implementation of the data-driven solutions is often not systematic, as well as partial and not integrated with each other. The system of smart waste collection works well in Barcelona (see Fig. 3) where the special ultrasonic sensors mounted in the waste containers allow to define the degree of filling of the container, which enables to plan routes accordingly. That is to say, the smart bins detect the amount of waste they contain and the sanitation workers plan their collection routes in line with the data they receive from the bins. The resulting optimization of routes reduces harmful emissions by waste collecting machines. This system has a number of benefits in Barcelona, including reducing time spent on the collection of waste thanks to the optimization of movement of waste disposal means, which in turn allows decreasing costs for fuel consumed during the collection of waste (Nikitin et al. 2016). Moreover, some bins connect directly to the underground repositories; waste is sucked out by vacuum via underground pipes, which reduces the noise and congestion caused by garbage collection trucks. The energy generated from waste incineration is used for the city's heating system. More advanced uses of such energy are typically associated with smart eco-cities (see Bibri 2020b; Bibri and Krogstie 2020 for examples of practical cases). In addition, the application of the data-driven technology involves the integration of the information collected on projects into the development and redevelopment of urban infrastructure (Nikitin et al. 2016).

Furthermore, the implementation of the smart grid solutions in Barcelona and London entails a variety of operation and energy measures, including smart meters, smart appliances, and energy efficient resources. The smart grid system is cost-effective, secure, and sustainable. It integrates and coordinates energy production, consumption, supply, and facilities through enabling technologies, energy services, and active users. In Barcelona, the MONICA project develops a system capable of precisely establishing the status of the distribution grid in real time and at any given moment (Status Estimator), which provides real and immediate information about the impact on the quality and safety of the supply (Nikitin et al. 2016). This project deploys an entire network of medium and low voltage sensors that record measurements for all the electrical variables needed to be entered in the grid's new Status Estimator. This receives the collected data in real time via the deployed sensors and the existing smart meters diagnosing the different problems on the grid in order to prevent them or improve them, as applicable.

Among the data-driven smart applications pertaining to the smart grid system are:

- Supporting decision–making as regards the generation and supply of power in line with the actual demand of citizens and other consumers to optimize energy efficiency and thus achieve energy savings.
- Optimizing power distributed networks associated with energy demand and supply.
- Monitoring and analyzing energy consumption and Greenhouse Gases (GHG) emissions levels in real time across several spatial scales and over different temporal scales, as well as enhancing the performance and effectiveness of the power system.
- Managing distribution automation devices to improve the efficiency, reliability, and sustainability of power production and distribution.
- Avoiding potential power outages resulting from high demand on energy using dynamic pricing models for power usage by increasing charges during peak times to smooth out peaks and applying lower charges during normal times.
- Avoiding the expensive and carbon–intensive peaks in power grid using new ways of coordination with regard to the overall ensemble of users and consumers.

In addition, London and Barcelona use a number of data-driven smart applications for energy management (Bibri 2020a), which allow:

- Citizens to have access to live energy prices and adjust their use accordingly;
- The use of pricing plans in accordance with energy demand and supply models;
- Consumers to manage their usage based on what they actually need and afford;
- Self–optimizing and –controlling energy consumption through integrating sensing and actuation systems in relation to different kinds of appliances and devices for balancing power generation and usage;
- Users to remotely control their home appliances and devices based on the IoT by means of such advanced functions as scheduling, programming, and reacting to different contextual situations; and
- Energy systems to gather and act on near real–time data on power demand, consumption, and generation from end–user connections (information about producers and consumers' behavior).

Environment

The importance of the environment in modern cities can be justified by the fact that the latter occupy 2% of the world's surface, have more than 50% of the world population, consume 70% of global energy supply, and generate 75% of GHG emissions. It is clear that we can have a major positive impact on the environment by making cities more sustainable and greener thanks to the evolving digitally and computationally augmented urban environments that could change our relationship with nature by, for example, consuming less natural resources and protecting the environment.

In Barcelona, advanced technologies allow, thanks to the city's Wi-Fi-network, real-time tracking of the quality of the air in terms of the presence of various substances as well as applying preventive measures in a timely manner, in addition to monitoring the condition and composition of green space in urban areas (Nikitin et al. 2016). The real-time data collected about the air quality in the city are analyzed to determine the impact of the solutions that have been adopted in terms of improving environmental conditions, as well as to identify the areas where further actions are needed. Barcelona leads compared to London in the air quality by using a number of pollution prevention systems, including forecasting and modelling based on advanced machine learning techniques (Bibri 2020a). As to London, as stated in the Smart London Plan (London City 2016), it aims to have the best air quality of major cities of the world by 2020, which will require significant reduction in GHG emissions from the city's transport sectors, as well as to become a zero-carbon city by 2050. According to Nikitin et al. (2016), five «living laboratories» were created across London, where sensors measure a range of physical parameters, including air quality and human activity.

Furthermore, the analysis of the information on the noise levels in London is of a less common trend compared to Barcelona where local projects of this type are active today. Implemented in Barcelona is low-cost sensors that detect noise levels and pollution, aiding in identifying and countering violations of the city policy in this regard. The smart noise control solution used in Barcelona enables to optimize and centralize the collection, integration, processing, analysis, and dissemination of information by the noise sensors of different suppliers and sound level meters distributed throughout the city (Nikitin et al. 2016).

Civic security

The most common technology present in London and Barcelona are smart policy and applications for messages on incidents by residents. Also, the installation of closed-circuit television (CCTV) cameras is used in London to send signals to the emergency services in the event of unforeseen situations on the road. CCTV is moreover used to detect incidents and provide queuing alerts (London City 2018). In Barcelona, Citizens' Postbox is a mobile app that one can use to report incidents in real time occurring anywhere in the city (Nikitin et al. 2016). However, several European cities, including London and Barcelona, are launching platforms based on the IoT and multiple sensors to collect the data to build smart cities through lighting. Accordingly, most of the smart projects in Europe involving the use of incident detection technology in street lights are pilot. Such technology, partially implemented in Rotterdam, uses smart microphones with advanced pattern recognition to monitor the safety of citizens and quickly react to crimes in response to the requests made by the residents in their neighbourhood (Forsdick 2019b). This system is associated only with shots from firearms recognition system in London (Bibri 2020a).

Citizen participation

Another technology implemented in London and Barcelona is crowdsourcing platforms, which is intended to address a number of issues related to different city areas. For example, citizens are being actively involved in solving urban problems to improve the efficiency of services and to enhance environmental performance in both cities (Bibri 2020a). The intent of London City (2018) is that technology innovators and entrepreneurs can help develop new approaches to service delivery. Barcelona launched Open Government portal to improve the transparency of the city management, where a number of initiatives have been realized with respect to engaging citizens in the solutions to the city issues (Nikitin et al. 2016).

The Smart London Plan (London City 2016) aims to put citizens at the center, with access to open data, leveraging the technology and creative talent of the city to enable it to better serve its citizens and to respond to their needs through increasing data sharing and analytics. London seeks to become a people-centric smart city (Misra 2018). It also aims is to explore ways of scaling up innovation, across administrative boundaries, to address the shared challenges of the city, such as waste collection and service delivery. Moreover, London City (2018) plans to establish a Smart London platform to allow citizens to feedback, rate, and shape the type of the experiences they want to have. In addition, London has established a number of digital literacy programs, and even investigated the reasons behind the digital exclusion of minorities and vulnerable groups (Eden Strategy Institute 2018). The London's new plan and Vision 2020 has digital inclusion focus as a core component of its strategy. The overall aim of the Government's Digital Inclusion Charter is to have everyone online, or with the aspiration to be online by 2020.

Barcelona actively involves citizens in policy decisions and in the development of services in the context of the smart city. With this commitment to citizen involvement, coupled with a strong technology platform, Barcelona is performing well in regard to leveraging smart technologies for the benefit of its citizens. Human capital is of utmost importance for future development and for building the smart city for smart people and by smart people, encouraging active citizen engagement in policy development and urban planning. The smart city strategy of Barcelona is empowering the citizens (Forster 2018). In 2015, Barcelona created several platforms for citizen participation in the technology and policy of the smart city (see Table 3).

Additionally, to improve the convenience of public services received by the citizens, City Council was created to allow the provision of services by public agencies remotely and mobile kiosks, where one can receive various certificates, publish a complaint, get necessary information, and so on (Nikitin et al. 2016).

All in all, the citizens are being offered more opportunities by new technologies to participate in the functioning of their communities. This enables the convergence of the physical and the digital-to-people. This is due to the fact that the digital changes can happen without heavy infrastructure, unlike the broad projects of the past that are determined by governments. Such changes can arise from bottom-up actions thanks to the right platforms through which people can transform the cities they belong to.

The challenge to resolve in developing data-driven sustainable smart cities that can benefit the quality of life of all citizens is that the tools we shape also shape us. In this respect, there is an increasing tendency to engage more citizens to take part in formulating policies through new technologies. It is clear that the citizenry as informed and

Table 3 Platforms for citizen participation in Barcelona. Source: Bibri (2020a)

Fab Labs	Classrooms where citizens can learn about the principles and applications of digital technologies, and gain access to tools that allow them to innovate technologically and participate in smart city projects.
22@Barcelona	A space designed to attract startups and skilled innovators to develop new technologies leveraging the data produced by the city's extensive IoT infrastructure. This has led to several successful pilot projects, including mobility and parking.
Cisco Barcelona Co-Innovation Center	Enables close collaboration among local Cisco customers, governments, startups, academia, and developers to create new business models, innovative ideas, and technological solutions.
Decidim.Barcelona	A participatory democracy platform which allows Barcelona's citizens to see and discuss proposals put forward by the city government, and submit their own. Decidim is used to create Barcelona's government agenda, with over 70% of proposals coming directly from over 40,000 participating citizens.

empowered through the Internet is increasingly making a difference as new forms of data and advice are being implemented by means of different participative and interactive platforms. Mobile and other applications are giving rise to new forms of preference elicitation, marking profound changes that need to be mobilized through the equally powerful big data science and analytics that advanced ICT will offer.

Urban planning

The use of the data-driven approach to urban planning, the analysis of the data related to the population, allows London and Barcelona to consider the emerging demand for various venues. In other words, the application of the data-driven technology in planning is associated with the planning of districts, streets, as well as urban infrastructure based on the collection of information on the movement of residents and activities. The Mayor's Smart London Plan developed in 2013, which outlines how big data technologies can be used to improve citizens' lives and includes measurements of success and targets accordingly, was updated in 2016, outlining the progress in different city areas (Pozdniakova 2018). According to the Smart London Plan, the city plans to "promote smart approaches through London's planning system—maximize the use of data to guide the planning and design of London, including in London's opportunity areas, and encourage developers to adopt a more consistent approach to deploying digital infrastructure to future proof new developments" (London City 2018, p. 11). Sustainable urban planning should involve the integration of information on the expectations and uses of the residents of the different districts of the city in the construction of scenarios in response to the need for urban renewal, redevelopment, and development. Such integration makes it possible to improve the way the districts meet the needs of their inhabitants and to associate and share environmental and social practices and enhance participation and dialogue with the residents.

In relation to planning in general, among the core questions that could broaden our knowledge on how data-driven sustainable smart cities can harness their potential through the underlying strategies and solutions are (Bibri 2020a):

- At what stage of the planning process should environmental, economic, and social concerns introduced, and what kind of measures are needed to have an effective integration of such concerns early on?

- To what extent can advanced technologies support joined-up planning, a form of integration and coordination which enables system-wide sustainability effects to be tracked, understood, analyzed, and built into the very responses and designs characterizing the operations and functions of the data-driven sustainable smart city?
- What kind of advanced technologies are available that can be implemented to make the planning process more dynamic based on constantly updated information on the operations and functions of the data–driven sustainable smart city?
- To what extent can the aggregation of real-time data contribute to dealing with changes in the data-driven sustainable city at any spatial and time scale, especially datasets can show the real-time functioning of the city and provide deep insights into how long term changes can be detected?
- To what extent can short–termism in urban planning, which entails measuring, evaluating, modelling, and simulating what takes place in the city over hours, days, or months, change the way the data-driven sustainable smart city functions as to focusing on sustainability problems and issues much more in the short term than hitherto?
- What is the potential of using urban intelligence functions to capture how the data-driven sustainable smart city is changing in its nature on the basis of its real-time functioning and becomes able to exploit and integrate complexity science, urban science, and big data science in constructing new powerful forms of urban simulations models and optimization and prediction methods that can generate more effective urban structures, forms, and scales?

With respect to the latter, urban intelligence and planning functions envisaged for the data-driven sustainable smart city as related to its processes and practices should be woven into the fabric of existing institutions whose mandate is advancing sustainability, optimizing efficiency, strengthening resilience, improving equity, and enhancing the quality of life for citizenry.

In sum, the data show the contours of a goal hierarchy in the data-driven sustainable smart city. Environmental and economic concerns are at the top of the goal hierarchy supporting the strategies of such city. In other words, the environmental and economic goals of sustainability dominate over the social goals of sustainability. The environmental and economic dimensions of sustainability is at the core of the agenda of urban development for London and Barcelona. This is a shortcoming since the social aspects are highly important in the urban context. Smart London Strategy Officer Dr. Stephen Lorimer said: “A lot of us fall into the trap of focusing on the environmental side of things but smart city development gives us an opportunity to be cross-cutting and address all three dimensions of sustainability” (Forsdick 2019a). The hierarchy of sustainability goals could reflect the challenge of incorporating social issues into a data-driven technology–led approach. These cities need to develop a broader agenda entailing an amalgam of environmental, economic, and social concerns. And in order to fully achieve their goal of becoming data-driven sustainable smart cities, the social aspects of sustainability need to be supported by planning practices and concrete development strategies.

Big data applications are associated with the three dimensions of sustainability in terms of enhancing and advancing urban processes and practices (Bibri 2019b, 2020a). Smart London Strategy Officer Dr. Stephen Lorimer said: "We need to build up a picture of what people's needs are in the city and how we can deliver a sustainable and fair city from that …. Data is the best way of articulating those needs, but we need to develop more than just our data sharing and data analytics—we need collaboration across environment departments and London Boroughs … We have been looking into opening up the data that are held by commercial and residential property owners to build a building stock model for London. The data can be used to develop good designs and master planning to increase social, economic, and environmental sustainability" (Forsdick 2019a).

Data-oriented competences

At the core of data-driven sustainable smart cities are various technical and institutional comptences, i.e., the set of demonstrable characterisitics and abilities that enable and improve the efficiency and performance of urban operational functioning, management, and planning as a collection of interrelated processes and activities. These competences are key features of London and Barcelona as illustrated in Table 4.

Urban operating systems/horizontal information platforms

Urban operating systems serve to link together diverse smart technologies to coordinate urban systems and domains. Smart cities represent constellations of instruments across many scales that are connected through multiple networks augmented with intelligence, which coordinate continuous data regarding the different aspects of urbanity in terms of the flow of decisions about the physical, environmental, economic, and social forms of the city. Examples of city operating systems or control rooms include Microsoft's CityNext, Urbiotica's City Operating System, IBM's Smarter City, and PlanIT's Urban Operating System, with the latter representing Enterprise Resource Planning (ERP) systems as intended to operate and coordinate the activities of large companies repurposed for cities (Bibri 2019b). Accordingly, this kind of instrumentation is the domain of the ICT industry that is offering the detailed hardware and software to provide the operating system for smart cities.

Barcelona is recognized for its best practices in accordance with the notion of the data-driven city. Horizontal information platforms, a form of city operating systems which aggregate and standardize the flows of functional data for their subsequent integrated analysis, operate in Barcelona under Sentilo and City OS. Sentilo, an open (data source) platform which connects all the sensors installed in the city and integrates all

Table 4 Data-oriented competences of London and Barcelona. Source: Adapted from Nikitin et al. (2016)

Competences	London	Barcelona
Analytical centers	• Smart City Board	• Big Data Center of Excellence
Horizontal information systems	• System implemented partially/pilot	• City OS • Sentilo
Training centres and programmes, urban information studies institutes	• City Univercity London • College London • Tech City Institute	• Institut Municipal d'Informatica

the data obtained from these sensors, constitutes a source of data for City OS. This open system in turn integrates and processes all the data obtained from systems of state control (traffic, mobility, energy, noise level, etc.), state agencies (schools, hospitals, cultural institutions, etc.), business environment, municipal sources, and various detectors and cameras. City OS project was developed in 2013 to solve the problems of data disconnection. Application developers can leverage Sentilo to gain access to sensor data in a more structured and convenient manner. Sentilo has been successfully deployed by other city councils that followed the lead of Barcelona. Similarly, a horizontal information platform in London has recently been developed at London DataStore (Bibri 2020a). This is one of the first platforms to make public data open and accessible, and has been operating since 2010. Open data are at the center of London's transition into a smart city (Card 2015). However, Ferro and Osella (2013) provides an overview of different open data models that can be used by municipalities or governments to release a variety of administrative and operational data.

The introduction of a horizontal information platform that integrates all the systems and technological solutions that are used in all the departments of Barcelona and London is a key solution to one of the significant challenges concerning the implementation of the data-driven approach to the smart city. This challenge pertains to the sectoral fragmentation of the deluge of urban data. The flows of this deluge generated by various functional departments is analyzed in isolation, whereas urban problems are of a complex and wicked nature and thus requires a rather comprehensive solution. The situation is usually compounded by the self-contained and unconnected nature of the technological solutions and information systems used in the different departments of the city.

Urban operations centers, dashboards, and strategic planning offices

Generally, urban operations centers and urban dashboards are intended to draw together and interlink urban big data to provide an integrated view and synoptic intelligence of the city (e..g., Bibri 2019b, 2020a; Kitchin 2014; Kitchin, Lauriault, and McArdle, 2015). Urban operations centers are typically created to monitor the city as a whole; pulls or draws together real–time data streams from many different city agencies and departments (including public transport and traffic, mobility, power grid, municipal and utility services, emergency services, weather feeds, information sent in by the public via smartphones, and social media networks) into a single data analytical center; and then process, analyze, visualize, and monitor the vast deluge of live service data for real-time decision-making and problem solving.

Analytical centers have been established and currently operate in both Barcelona under Big Data Center of Excellence as well as in London under Smart City Board. As to Barcelona, the center is committed to create innovative platforms for the promotion of big data use and application, the introduction of big data technologies, and the provision of expert assistance (Nikitin et al. 2016). It was also planned to open Cisco innovation center for the Internet of Everything in 2026. As regards London, the Smart London Board, which involves industry experts, entrepreneurs, and thought leaders, was set up to support the city authorities in visioning, strategizing, and applying smart city objectives (Bibri 2020a; Eden Strategy Institute 2018). In addition, the London

Fig. 4 CASA's London City Dashboard. Source: http://citydashboard.org/london

DataStore plays an important role in overcoming city challenges, allows keeping citizens up-to-date, and helps to create applications based on the raw data available thanks to the open access to the public data that are being used to control, regulate, and plan the city. According to the Smart London Plan (2018, p. 6), the London Datastore "has engaged London's developer community and resulted in numerous apps that help the city to function better. We will build on this work to identify and publish data that addresses specific growth challenges, with an emphasis on working with companies and communities to create, maintain, and use these data."

Urban dashboards generate visualisations that help both expert and no-expert users interpret and analyze information. In London, city dashboards communicate live feeds of real-time data to citizens. As illustrated in Fig. 4, citizens can be informed in real-time about the weather, air pollution, public transport delays, electricity demand, public bike availability, traffic, and so on. The London dashboard as a visualisation site relies on data, though not in real-time, to track the performance of the city with respect to a number of areas—including, but not limited to, transport, environment, communities, housing, health, jobs and economy, and policing and crime (Kitchin 2014).

In the context of data-driven sustainable smart cities, which develop and use a sort of integrated, real-time urban data analytics, analytical centers, dashboards, and applications provide a powerful means for not only making sense and conceiving of, living in, and managing the city in the here-and-now, but also for planning the city in relevance to sustainability. Planning involves, among others, envisioning future scenarios as regards how the city should perform sustainably on the basis of data-driven technological solutions.

Strategic planning offices are key to urban development projects and endeavors, especially when it comes to sustainability. They are part of the competences of London and Barcelona in regard to applied data-driven technology. Both cities promote smart approaches through planning systems—make extensive use of data to guide urban planning and design and to encourage developers to deploy digital infrastructure to future proof new developments. Strategic planning and policy offices use a one-stop data analytic hub to bring and weave together data from a variety of city agencies and departments for the management and planning of the city in a more efficient and effective way (Bibri 2019b). Huge amounts of data stream daily through such offices for analysis in terms of cross–referencing data, identifying patterns, and recognizing and solving city problems.

Training programs and educational institutes

Specialized academic programs within data science and big data analytics related to urban science, urban computing, urban studies, urban analytics, and so on have gained widespread use in not only the Cities of London and Barcelona, but in many other cities in developed countries. Barcelona is one of the very few cities where the Institutes of Urban Computing have been established to study the city management issues in a systemic way using advanced big data analytics techniques, and a large number of educational programs with big data analytics disciplines and the introduction of technologies for city management are offered by universities and business schools (Nikitin et al. 2016). In London and Barcelona, numerous initiatives have, yet at varying degrees, been implemented to develop competencies in a number of areas related to big data analytics and urban informatics/science by educating citizens and accumulating relevant expertise thanks to the creation of the related centers. These involve conducting seminars and courses and providing trainings to improve the level of technological knowledge considering the solutions being implemented in the city and used by citizens. In addition, the Smart City Business Institute (SCBI) was set up in Barcelona to introduce what is known as smart education to elementary, middle, and high schools, offering hands-on workshops to help students develop mobile and robotic apps that attend to smart city challenges (Eden Strategy Institute 2018).

At the practical level, much needs to be done for big data analytics projects to become successful in terms of studying, managing, and planning cities. In fact, many of these projects are still having difficulties to deliver useful and concrete outcomes in this regard. This is due often to the poor management and utilization of available resources, in addition to the lack of the training of the data analysts. Big data science and analytics is a heavily applied field where the programs offered by academic institutions are inadequate for preparing the data scientists and analysts for the task (Bibri 2019d ; Donoho 2015).

Innovation labs/Research centers

Innovation labs and research centers are springing up everywhere, becoming commonplace across different cities. Within the scope of this paper, they indicate the degree of implementation of the data-driven city concept in terms of the extent to which the applied technology solutions are developed for urban operational functioning, planning, and management. Therefore, a number of cities in developed countries have established innovation labs and research centers, thereby stimulating actively the development of innovative solutions. These are known in London as ICT Labs and Future Cities Catapult, and in Barcelona as Cisco IoE Innovation Center and city districts (Nikitin et al. 2016). In this context, they serve as the ground for testing potential solutions for the management of the city. For example, ICT Labs are concerned with developing and implementing advanced solutions for urban management. In addition, the new London Office for Technology & Innovation (LOTI) was set up to understand, enhance and apply the leading city practices, as well as to integrate resources and expertise for the benefits of the whole city through collective intelligence (Bibri 2020a; Eden Strategy Institute 2018).

An innovation lab in this context denotes a working space designed to develop, test, and improve innovative solutions for sustainability in the form of urban intelligence functions. It is a unique environment devoted to building, advancing, and sharing practical knowledge and know-how in response to the needs and aspirations of the city and its stakeholders and citizens. It involves researchers, scientists, industry experts, business professionals, and citizens. The key strengths lie in the team's multidisciplinary knowledge and skills, long–standing experience, international expertise, and access to global networks in the sphere of sustainability and related technologies.

Generally, advanced ICT is being used to increase the efficiency of energy systems, optimize the performance of green technologies, enhance the delivery of public and social services, advance transport and traffic systems, and improve the quality of life, but to name a few. In this respect, the real challenge for modern cities is to explore the notion of data-driven sustainable smart cities as innovation labs. This entails developing novel intelligence functions for the city based on the IoT and big data technologies for enhancing urban practices in response to the challenges of sustainability and urbanization. Especially, the vision of the city functioning in real time is becoming increasingly achievable and deployable (e.g., Kitchin 2014; Rathore et al. 2018).

Table 5 provides a summary of the competences and related functions of the two emerging data-driven smart cities for improving different areas of sustainability.

Infrastructure and data sources

In the face of the escalating rate and scale of urbanization, we need not only to develop new urban fabric that can deal effectively with this growth, but also to make the best use of the existing infrastructural and informational assets to ensure that the increasingly large metropolises are sustainable by means of advanced technologies. In this respect, the IoT has been massively used to available resources of different kinds, buildings, and infrastructure without many engineering obstacles with existing cities.

There are different indicators of the readiness of a city as to the implementation of the data-driven city concept in smart urbanism. These indicators are associated with both the technical and institutional aspects of the city competences. The focus here is on the degree of the readiness of London and Barcelona from a technical perspective in terms of the availability and development level of the city infrastructure and data sources that are needed to generate and transmit data to the diverse city centers for

Table 5 Data-driven smart city competences and related functions

Competences	Functions
Horizontal information platforms	• Linking together multiple technologies to enable greater coordination of urban systems and domains: - Connecting all the sensors installed in the city and storing and integrating all the sensed data - Aggregating and standardizing the flows of the functional and territorial data from the systems of state control, business environment, municipal sources, and numerous sensors and cameras for their subsequent analysis and visualization in 3D format - Reworking and repackaging the collected data for daily consumption by different city stakeholders - Allowing application developers to gain access to the sensed data in a more structured and convenient manner - Providing comprehensive solutions to complex urban problems by integrating the self-contained and unconnected technological solutions and information systems used in different functional departments • Improving the efficiency of the implemented applied technological solutions by means of the functionally compatible information platforms
Operations centers and dashboards	• Drawing together and interlinking real–time data streams to provide an integrated view and synoptic intelligence of the city: - Using visualization sites to help both expert and no-expert users interpret and analyze information, and to allow citizens to monitor the city for themselves and for their own ends - Relying on integrated, real-time data to track the performance of the city and to communicate the live feeds of real-time data to citizens with respect to a number of areas - Using automated systems to respond to citywide events by making immediate decisions pertaining to various urban areas - Overcoming urban challenges, keeping citizens up-to-date, and developing applications based on the standardized and published open data thanks to the horizontal information platforms • Creating innovative platforms, promoting big data use and application, introducing data-driven technologies, and providing expert assistance
Strategic planning and policy office	• Making extensive use of data to guide urban planning and design, and to encourage various developers to deploy digital infrastructure to future proof new developments • Using a one-stop data analytic hub to bring and weave together data from a variety of city agencies and departments in order to regulate and govern the city in a more efficient and effective way • Cross–referencing data, identifying patterns, and recognizing and solving city problems
Training and educational programs and institutes	• Providing specialized academic programs involving big data science and analytics within such domains as urban science, urban informatics, urban computing, urban analytics, and urban studies • Offering a large number of educational programs with big data science and analytics disciplines and introducing technologies for city operational functioning, management, and planning • Implementing initiatives for developing competencies in a number of big data science and analytics areas in relation to urban sustainability by conducting seminars and providing trainings to improve the level of technological knowledge in this regard
Innovation labs and research centers	• Creating multidisciplinary teams based on practical know how, long–standing experience, international expertise, and access to global networks • Enabling interaction and cooperation between scholars, researchers, industry experts, business professionals, and thought leaders to enhance research opportunities, academic excellence, real-world problem solving, and knowledge creation and dissemination • Developing and testing innovative technological solutions for urban operational functioning, management, and planning • Featuring the latest developments in urban technologies and solutions and demonstrating how they are applied in real-world settings • Developing urban intelligence functions for improving and optimizing urban operations, functions, services. designs, and strategies • Integrating resources and expertise for the benefits of the whole city through collective intelligence • Managing, analyzing and visualizing different kinds of urban projects • Supporting the city authorities in visioning, strategizing, and applying smart sustainable city targets and objectives

Table 6 Infrastructure and data sources rating

Infrastructure	*Unit*	*Barcelona*		*London*	
		Value	Score	Value	Score
1. Accessibility	Average mark		2.4		3.3
1.1. Density of the city Wi-Fi network	Pcs. / km²	5.79	4	No[2]	1
1.2. Share of households with internet access	%	70	2	94	5
1.3. Usage and coverage of mobile packet communication for citizens of the city	%	65	2	95	4
1.4. Level of penetration of the fibre-optic network	Rating value[1]	100	5	21	2
1.5. Number of Wi-Fi hotspots in private and corporate segments	Rating value	72	2	100	5
1.6. Tariffs for broadband Internet connection as a percentage of GDP per capita	Rating value	93	1	99	4
1.7. Tariffs for mobile Internet as a percentage of GDP per capita	Rating value	74	1	86	2
2. Quality	Average mark		2.0		5.0
2.1. Speed of fixed broadband in private and corporate segments	Mbps	16	3	25	5
2.2. Network capacity	Values in the rating	5	1	84	5

Sources	*Unit*	*Barcelona*		*London*	
		Value	Score	Value	Score
1. Open data and electronic payments	Average mark		2.3		4
1.1. Open data (OD) and online presence	Rating value[1]	84	3	100	5
1.2. Electronic and mobile payments	Rating value	331	2	930	4
1.3. Number of data sets on the OD portal	Pcs.	48	2	66	3
2. Residents	Average mark		2.4		3.6
2.1. Social network use	Rating value	59	1	91	5
2.2. Internet use as a percentage of the population	Rating value	83.7	3	90	4
2.3. Level of mobile penetration	Rating value	24	3	35	4
2.4. Proportion of computer owners	Rating value	74	2	90	5
2.5. Proportion of broadband internet subscribers in the private sector	%	84.5	4	59	1
2.6. Proportion of residents who own smartphones	%	59	2	89	5
2.7. Number of visitors of municipal services web-portal		24	2	4	1
3. Sensors and surveillance cameras	Average mark		4.8		4.5
3.1. Road traffic	Availability	Y	5	Y	5
3.2. Public transit	Availability	Y	5	Y	5
3.3. Parking	Availability	Y	5	Y	5
3.4. Electricity grid	Availability	Y	5	Y	5
3.5. Street lighting	Availability	Y	5	N	0
3.6. Cleaning and waste disposal	Availability	Y	5	Y	5
3.7. Air	Availability	Y	5	Y	5
3.8. Exhaust emission control	Availability	Y	5	Y	5
3.9. Water	Availability	Y	5	Y	5
3.10. Density of CCTV cameras	Pcs. / km²	32.2	3	318.1	5

Source: Nikitin et al. (2016)

analysis and then the deployment of the obtained results for various uses and applications in terms of decision-making. Nikitin et al. (2016) compare London and Barcelona using statistical analysis and expert assessment of technology implementation in terms of the degree of theirreadiness. Their results are presented in Table 6. The readiness of some elements were assessed based on the results of the Networked Society City Index rating from Ericsson. The higher the value is, the higher the level of the rated indicator.

It is worth noting that the sensor infrastructure is largely developed proportionally in London and Barcelona. A most popular form of government-sponsored Internet access is seen in the form of public Wi-Fi areas around the city. The Barcelona City's Wi-Fi has been built for quite sometime. Within the framework of the development of the city Wi-Fi in Barcelona, 590 spots among them 220 in parks have been installed only until 2016, and the number is planned to increase to 1520 new spots in order to extend the Wi-Fi network to cover all buses and underground (Nikitin et al. 2016). According to Eden Strategy Institute (2018), Barcelona has declared its intentions to become the most connected city in the world and it is following through on its promise by investing considerably in the IoT infrastructure and applications for the city. A city Wi-Fi can have a significant impact on the communication capabilities of the sensor infrastructure and the data transfer system. As regards the IoT sensors and the city's open data platform, Barcelona therefore has a dense network of sensors which compile data from a wide variety of sources. Barcelona has brought the IoT to life (Adler 2016).

There is a range of the ICT architectures that essentially aim to provide the appropriate infrastructure for the operation of the IoT and Big Data ecosystem in relation to large–scale technological solutions within smart cities. These city architectural designs tend to follow similar patterns in terms of layers. However, Sinaeepourfard et al. (2016) analyze Barcelona as a smart city, with special emphasis on the layers responsible for collecting the data generated by the sensors deployed across the city. The authors estimate the amount of the data transmitted daily via sensors through the network, and make a rough projection based on the assumption of an exhaustive deployment that fully covers the whole city. They state that the Barcelona City Council and Municipal Institute of Informatics (MII) jointly cooperated in 2012 to set the basics of an architecture defining the strategies and policies allowing Barcelona to become a Smart City. The design of the Barcelona Smart City IT architecture entails three main layers, namely the Information Sources layer, the Middleware layer, and the Smart Applications layer (see Fig. 5).

A successful system enabling the functioning of the data-driven smart city can be divided in three levels, namely:

- The infrastructure that collects the data within the framework of the city. This level includes technologies and solutions allowing the collection and transfer of the data for their further processing and analysis. Here the standardization of the data infrastructure and the data integration in a unified system are important for facilitating further usage and processing of the data (e.g., Sentilo).
- The tools dedicated for storage, management, processing, and analysis of the data collected by the system (e.g., City OS).
- The exchange of the data among all the interested parties and the adoption of solutions based on the analysed data. This level includes platforms with open data and tools of data visualization (e.g., dashboards) applied by the city administration

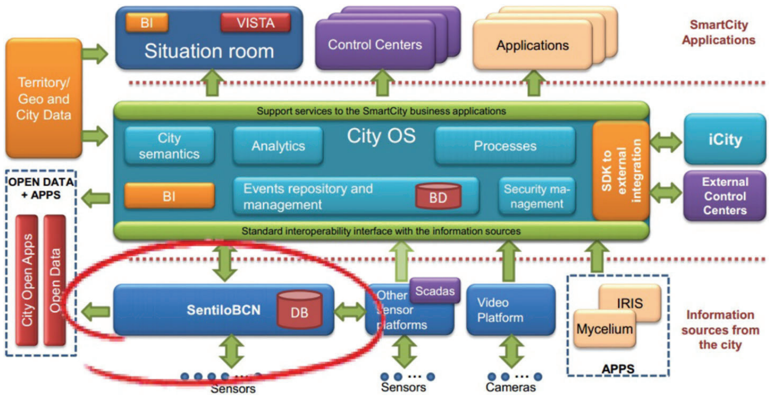


Fig. 5 Barcelona Smart City IT architecture. Source: Sinaeepourfard et al. (2016)

for control over the city management system, automated systems of response to city-wide events related to various urban systems (e.g., situation room and control centers), as well as a number of applications (e.g., service agencies and other developers).

The plan of London City (2018) is to ensure that it has one of the fastest wireless networks in the world and invests in free Wi-Fi in order to offer a smarter experience to all citizens. It has launched the fastest free Wi-Fi in all of UK with a multi-million-dollar investment, offering fast Internet speeds at 150 points across the city (Eden Strategy Institute 2018). London has 5969 public Wi-Fi hotspots across Greater London, and invested USD 2.32 million through the Super Connected Cities Program to offer indoor public Wi-Fi in Galleries and Museums (Eden Strategy Institute 2018). Indeed, London is leading as to the quality and availability of the broadband and mobile Internet compared to Barcelona. It is also leading in regard to the level of data disclosure: making public information known and accessible, particularly for improving sustainability in the city. London DataStore publishes open data from different departments of the city administration, and aggregates all data available on functional and territory data, analyze them, and visualize the results in 3D format. In London, the data are used most rapidly for making decisions pertaining particularly to transport management. The open data published by the transport administration entail the data that are collected in the real time mode, and the data obtained from various different operators are standardized and then published on the open data portal (Unified API) to be used by numerous developers of mobile applications, especially transport and mobility (Nikitin et al. 2016).

\In addition, in London around 78% of adults own a smartphone, 90% of population have access to the internet, free Wi-Fi are provided for over 80 public buildings and libraries, 40,000 businesses are digital, and 200,000 employees work in technology sector, high-speed affordable digital connectivity is a priority for the city (Pozdniakova 2018). Indeed, London is leading compared to Barcelona in terms of accessibility as a key feature of the city infrastructure as shown in Table 6. Furthermore, the government of London has defined rules and guidelines for its open data platform to work with public and private sector organizations, enable common data standards, identify and prioritize data needs, protect privacy, and guarantee a transparent use of data (Eden Strategy Institute 2018).

On the whole, both cities are finding multiple benefits to connecting devices and collecting a plethora of data that can be translated into meaningful insights to guide the cities' daily decisions. According to Cisco's estimates, Barcelona's current smart city investments should return a cumulative economic benefits of USD 970 million by 2026. So far, the IoT systems have saved Barcelona about USD 58 million on water, generated USD 50 million per year in parking revenues and generated 47,000 new jobs (Eden Strategy Institute 2018).

However, while modern technologies are adequately introduced for efficient and sustainable solutions within common areas of city management in the two cities, e.g., numerous methods applied for reducing the negative impact on the environment and lowering energy consumption, there still is a need for more applied technologies that can aid the city authorities in using the data to the full extent to make and enhance decisions related to sustainability. Generally, a colossal amount of the data needed to make a city sustainable smart is indeed already available, butit is simply a matter of knowing how to understand and exploit these data.

Discussion

The study has identified the core dimensions of the data-driven smart city based on combining and comparing London and Barcelona as the leading data-driven smart cities in Europe. Moreover, it has shown how these cities are utilizing data-driven technology solutions to improve their contribution to the different areas of sustainability. The data-driven sustainable smart city can be implemented on different spatial scales and within different urban systems and domains. This depends on the degree of technology development with respect to the instrumentation, datafication, and computation that need to pervade the urban environment, and how and to what extent these technological elements are leveraged in the transition towards sustainable development. As the two cities share and vary in these aspects, combining practical initiatives from both cities is meant to be of complementarity in the sense that these cities can improve each other's qualities and learn from each other's experiences.

From a comparative perspective, the comparison of London and Barcelona concerns the relative proportions of the implementation of big data technologies and the use of data-driven solutions in city systems and domains in the context of sustainability. In other words, this comparison focuses on the kind of problems and challenges that the two cities face, and what this entails in terms of the technologies they adopt based on the solutions they prioritize in regard to sustainability. Otherwise, the enabling, integrative, constitutive, and ubiquity nature of advanced ICT makes the latter applicable to different urban contexts in terms of the development, deployment, and management of big data technologies and their applications, irrespective of the complexity of physical, environmental, economic, and social systems of the city.

Worth pointing out is that every city has its specific opportunities, capabilities, and constraints, not least in relation to the application of advanced technologies for sustainability. Hence, there are many things for cities to learn from each other as regards the knowledge and expertise available in this regard. It is therefore crucial to investigate the innovative solutions and successful practices of different data-driven sustainable smart cities based on the ongoing and future endeavors and projects in their local context, and then compile and distill the results into a unified outcome that contributes to forming a basis for a model of urbanism that can be applied by different cities based on their own circumstances. This is one of the objectives that is intended to be achieved from conducting this study by comparing and combining London and Barcelona in their effort for becoming data-driven sustainable smart cities. In this context, lessons can be learned from both cities, particularly in relation to data-oriented competences. Especially, it is widely recognized that there cannot be a set of rigid strategic guidelines or strict solutions to be implemented anywhere around the world to achieve urban sustainability. Indeed, sustainability to a certain extent depends on several intertwined factors, which are usually shaped and influenced by the national and local contexts. Accordingly, the local opportunities, capabilities, and constraints of each city need to be dealt with in a more integrated given the complexity of urban systems in terms of their political, social, economic, and environmental dimensions.

Moreover, no attempt has, so far, been undertaken to establish any 'data-driven sustainable smart city' indexes, nor is there a single conceptual unit or analytical proposition of such city. To put it differently, there are as yet no cities that could be assessed by experts or scientists so to be able to unanimously assume basic standards of the data-driven sustainable smart city. Also, the heterogeneity of the concept of sustainability and the constant change of technological landscape remain problematic for the practical implementation of policies related to such city. There are no policy documents that provide concrete guidelines for global implementation. Accordingly, each city should deal with its own planning and development in the sense of designing the data-driven sustainable smart city, applying its solutions, adopting its strategies, and implementing its policies to improve the quality of life of its citizens. To add, indeed, city authorities, scientific communities, and industry experts have no common agenda of action.

Furthermore, data-driven sustainable smart cities as a holistic approach to urbanism is opening entirely new windows of opportunities to advance sustainability by using advanced technologies to enhance the process and practice of sustainable development. Among the most urgent issues they deal with are:

- Transport efficiency and management
- Traffic congestion
- Urban infrastructure management and resilience
- Security and safety
- GHG emissions
- Services enhancement
- Equal access to education, health, and other social services
- Citizen participation in urban management and planning

Big data technologies provide significant opportunities for transforming urban sustainability due to the huge potential of their novel applications that usher in intelligence in nearly all city systems and domains. In this respect, Bibri (2019b) highlights and substantiates the great potential of big data analytics for increasing the contribution of sustainable smart cities to environmental, economic, and social sustainability by identifying numerous practical applications of big data technology in relation to a number of urban systems and domains. The advantages of this advanced technology lie in how significantly it will influence sustainable smart cities and their citizens. Besides, the core enabling technologies of big data analytics will in the near future be dominantly used for monitoring, understanding, analyzing, and planning smart cities to improve their health and the life of their citizens. The emerging data-driven approach to smart urbanism is changing the way we understand, plan, and govern cities, both within and across city domains (Bibri 2019b, 2020a; Kitchin 2015; Kitchin, Lauriault, and McArdle, 2015; Townsend 2013),, The linking and integration of diverse forms of urban data provide a deeper, more holistic analysis, which makes it possible to control, manage, and regulate urban life on the basis of evidence-based facts, particularly in relation to sustainability, efficiency, resilience, equity, and the quality of life.

In addition, data-driven sustainable smart cities involves a number of data-oriented competences that need to be developed to enable the wide use of data-driven technological solutions in urban operational functioning and management as well as urban planning and development. These competences include urban operating systems, urban operations centers, urban dashboards, innovation labs, research centers, and training centers and educational institutes. One of the key innovations being utilized by these centers is open data movement, a form of data sharing among city actors in an attempt to improve many aspects of urban living. However, most of the identified data-oriented competences have partly been addressed by several studies in relation to smart cities of the future (e.g., Batty et al. 2012; Kitchin 2015, 2016; Townsend 2013), data-driven smart sustainable cities of the future (Bibri 2019a, b, 2020a), real-time cities (e.g., Kitchin 2014), and data-driven cities (Nikitin et al. 2016).

The idea of building data-driven sustainable smart cities is becoming a reality thanks to the recent advancements in both urban development practices as well as technological solutions. As with many emerging data-driven smart cities across the globe, London and Barcelona are increasingly pervaded with various forms of the IoT, namely sensors, platforms, infrastructures, applications, and networks that produce colossal amounts of data. This deluge provides rich streams of information about many aspects of urbanity, enables real–time analysis of urban dynamics, and facilitates new ways of how the city can be managed and planned. However, the IoT is known to involve significant security risks. A major hindrance in the broad integration of IoT in smart cities lies in its security. The IoT is inherently networked and ubiquitous. The larger the networks, the higher the security risks. Therefore, it is important to have secure IoT devices, platforms, applications, and infrastructures to avoid major catastrophes associated with massive breaches or attacks. Smart city technologies raise a number of cyber-security concerns that require careful consideration and special attention, although successful cyberattacks on cities remain relatively rare (Hashem et al. 2016). Most of the smart city strategies fall short in considering security risks. Such disregard can be attributed to the ambiguities in government laws and the lack of institutional and organisational policies (Almeida et al. 2017). Several studies have addressed security risks and proposed potential solutions to mitigate them in smart cities. For example, Lacinák and Ristvej (2017) provide insights into the importance and use of modeling and simulations to address security issues. Khanac et al. (2017) identify a comprehensive list of stakeholders and modeled their involvement in smart cities by using the Onion Model approach, providing a secure service provisioning framework in smart cities. To guarantee a successful implementation of the IoT in smart cities, solving

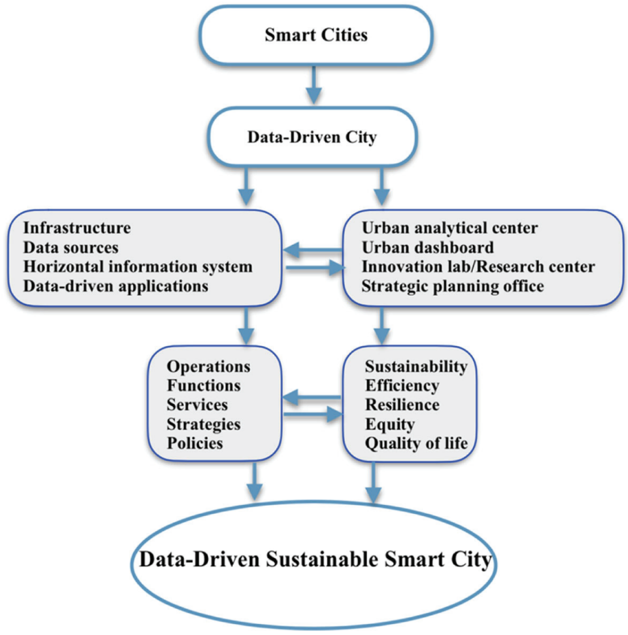


Fig. 6 A conceptual framework for data-driven sustainable smart cities

security issues must be given priority in the IoT realm. All in all, to deal with security issues requires both technical and socio-political solutions.

On the whole, this study has identified different themes, i.e., technologies, applications, competences, infrastructure, and data sources that are related to data-driven sustainable smart cities. The data collected from different sources show that different themes produce distinguished models of data-driven sustainable smart cities. One of the key factors determining the distinction between these models is the extent to which the goals of sustainable development are supported in the operation, management, planning, and development of the city. This entails the level of the development of different technological components and their implementation to improve and advance sustainability.

The integrated framework (Fig. 6) is derived from the results of the two cases investigated. Hence, its essential elements are based on the emerging paradigm of smart urbanism in terms of its data-driven and sustainable strands. As such, it attempts to capture in a structured manner the core dimensions of the data-driven sustainable smart city. In this respect, there are four basic categories of criteria that are used here in defining such city, namely technologies, competences, processes and practices, and sustainability and smartness. In addition, this framework represents a conceptual structure intended to serve as a guide for building different models of data-driven sustainable smart cities.

Conclusion

Big data technologies are certainly enriching our experiences of how cities function. And they are offering many new opportunities for more informed decision-making with respect to our knowledge of how to monitor, understand, analyze, and plan cities more effectively. Whether these developments will be to our collective advantage or disadvantage is yet to be seen for there is undoubtedly a dark side to all technological developments. Regardless, many smart cities across the globe have embarked on exploring and unlocking the potential of big data technologies for addressing and overcoming many of the pressing issues and complex challenges related to sustainability and urbanization. London and Barcelona are seen as exemplary practical initiatives in data-driven sustainable smart urbanism on national, European, and global scales. This study has been carried out as a demonstration endeavor of what these two cities are renowned for in this regard, with the aim of being exposed to general lessons. It has been worth illustrating the potential underlying the development and use of big data technologies for advancing sustainability.

The aim of this paper was to investigate how the emerging data-driven smart city is being practiced and justified in terms of the development and implementation of its innovative applied solutions for sustainability. This study shows that these cities have a high level of the development of the applied data-driven technologies, but they slightly differ in the level of the implementation of such technologies in different city systems and domains with respect to sustainability areas. They also moderately differ in the degree of their readiness as to the availability and development level of the competences and infrastructure needed to generate, transmit, process, and analyze large masses of data to extract useful knowledge for enhanced decision making and deep insights pertaining to urban operational functioning, mangement, and planning in relation to sustainability. Barcelona has the best practices in the data-oriented competences, whereas London takes the lead in regard to the ICT infrastructure and data sources.

Furthermore, the data–driven sustainable smart approach to urbanism as practiced by the two cities is justified by its ability to contribute, at varying degree, to the different areas of sustainability. However, the environmental and economic goals of sustainability dominate over the social goals of sustainability with respect to the development and implementation of the data-driven smart solutions for urban processes and practices.

Given the enabling, integrative, constitutive, and ubiquity nature of big data technology as an advanced form of ICT, coupled with the universality of urbanization and sustainability as major global shifts at play today, the findings of this study can be generalizable and thus applicable to other cities in terms of the implementation of data-driven technology solutions for the management of the city. In regard to the specificity of the findings of this study, the focus should be on the kind of applied solutions other cities should prioritize based on the challenges they face as to sustainability and urbanization, as well as their financial resources and technological capabilities. Still, to successfully implement and manage big data technology requires a holistic perspective so as to be able to identify and manage gaps and conflicts, as well as to harness synergies between different technological components with respect to functionality, ownership, access, and governance.

This research enhances the scholarly community's current understanding of the emerging phenomenon of the data-driven city with respect to the untapped synergic potential underlying the integration of smart urbanism and sustainable urbanism for improving sustainability. Highlighted by this research is the interplay between these two approaches in terms of producing combined effects that are greater than the sum of their separate effects as regards the benefits of sustainability thanks to the big data revolution. Previous studies have long criticized smart cities for falling short in incorporating the goals of sustainable development in their strategies, and, more recently, for overlooking the role of data-driven solutions in sustainable development. This study draws special attention to the benefits of the emerging paradigm of big data computing as to transforming the future form of smart cities in relation to sustainability. Furthermore, this study will help strategic city actors understand what they can do more and invest in to enhance the sustainability performance of their cities on the basis of the applied data-driven solutions. It will also give policymakers an opportunity to identify areas for further improvement while leveraging areas of strength as to the data-oriented competences and infrastructure.

We hope that this study has produced the kind of the results that will be useful in directing further research by providing the grounding for more in–depth investigation on data-driven sustainable smart city development. We would particularly like to encourage qualitative research of the kind that we have attempted, which try to illuminate the core dimensions of the data–driven sustainable smart city and the assumptions and claims behind related initiatives. The rationale for this is that as the demand for practical ideas from the technological advanced nations about how to meet the requirements of sustainability through data–driven smart urban development increases, those initiatives are likely to attract attention from strategic urban actors around the world. Further research should focus on providing the knowledge that such actors will need to make informed decisions about how to achieve the objectives of data-driven sustainable smart cities in their own context. By investigating the two cities, we sought to offer models of big data technology-led urban transformation for other cities to learn from. Moreover, as this study has demonstrated that applied technological solutions already exist across the selected cities, it would be extremely useful to conduct a wider and more varied comparison involving cities from other European countries and from the rest of the world with a view to revealing more general trends in urban planning and development. In addition, a sequel to this work and thus part of our own future research is to integrate the data–driven smart city, the eco–city, and the compact city as the leading paradigms of urbanism into a novel model in order to improve and advance sustainability. This is one among many opportunities that can be explored towards new models of sustainable cities, predicated on the assumption that there are multiple pathways to and strategies for achieving the vision of sustainable development. Lastly, we believe that the outcome of this study can help advance the understanding of how the smart city phenomenon is evolving and adapting to new global shifts, especially in regard to sustainability.

Abbreviations
CCTV: Closed-Circuit Television; ERP: Enterprise Resource Planning; GHG: Green House Gases; GPS: Global Positioning Systems; ICT: Information and Communication Technology; IoT: Internet of Things; LED: Light Emitting Diode; LOTI: London Office for Technology & Innovation; MII: Municipal Institute of Informatics; MODA: The Mayor's Offices of

Data Analytics; MOTI: The Mayor's Offices Technology and Innovation; NFC: Near-Field Communication; RFID: Radio Frequency identification; SCBI: Smart City Business Institute; ULEZ: Ultra Low Emission Zone

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S.E.B. designed the research, conducted the literature review, collected and analyzed the data, and wrote the manuscript. J.K reviewed the manuscript. The authors have read and agreed to the published version of the manuscript.

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Paper 9

Environmentally Data-driven Smart Sustainable Cities: Applied innovative Solutions for Energy Efficiency, Pollution Reduction, and Urban Metabolism

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RESEARCH

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Environmentally data-driven smart sustainable cities: applied innovative solutions for energy efficiency, pollution reduction, and urban metabolism

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Abstract

The IoT and big data technologies have become essential to the functioning of both smart cities and sustainable cities, and thus, urban operational functioning and planning are becoming highly responsive to a form of data-driven urbanism. This offers the prospect of building models of smart sustainable cities functioning in real time from routinely sensed data. This in turn allows to monitor, understand, analyze, and plan such cities to improve their energy efficiency and environmental health in real time thanks to new urban intelligence functions as an advanced form of decision support. However, prior studies tend to deal largely with data-driven technologies and solutions in the realm of smart cities, mostly in relation to economic and social aspects, leaving important questions involving the underlying substantive and synergistic effects on environmental sustainability barely explored to date. These issues also apply to sustainable cities, especially eco-cities. Therefore, this paper investigates the potential and role of data-driven smart solutions in improving and advancing environmental sustainability in the context of smart cities as well as sustainable cities, under what can be labeled "environmentally data-driven smart sustainable cities." To illuminate this emerging urban phenomenon, a descriptive/ illustrative case study is adopted as a qualitative research methodology§ to examine and compare Stockholm and Barcelona as the ecologically and technologically leading cities in Europe respectively. The results show that smart grids, smart meters, smart buildings, smart environmental monitoring, and smart urban metabolism are the main data-driven smart solutions applied for improving and advancing environmental sustainability in both eco-cities and smart cities. There is a clear synergy between such solutions in terms of their interaction or cooperation to produce combined effects greater than the sum of their separate effects—with respect to the environment. This involves energy efficiency improvement, environmental pollution reduction, renewable energy adoption, and real-time feedback on energy flows, with high temporal and spatial resolutions. Stockholm takes the lead over Barcelona as regards the best practices for environmental sustainability given its long history of environmental work, strong environmental policy, progressive environmental performance, high environmental standards, and
(Continued on next page)

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ambitious goals. It also has, like Barcelona, a high level of the implementation of applied data-driven technology solutions in the areas of energy and environment. However, the two cities differ in the nature of such implementation. We conclude that city governments do not have a unified agenda as a form of strategic planning, and data-driven decisions are unique to each city, so are environmental challenges. Big data are the answer, but each city sets its own questions based on what characterize it in terms of visions, policies, strategies, pathways, and priorities.

Keywords: Smart sustainable cities, The IoT and big data technologies, Data-driven smart solutions, Energy efficiency, Environmental pollution, Smart urban metabolism, Environmental sustainability, Smart grid, Policy, Stockholm, Barcelona

Introduction

The concentration of economic activities, the high-intensity use of resources, and the massive deployment of non-renewable energy in cities demonstrate that they have major negative impacts on the environment. In other words, the significance of the environment in cities is justified by the fact that they consume about70% of global energy supply, generate about 75% of greenhouse gases (GHG) emissions, and have currently more than 50% of the world population (Bibri and Krogstie 2020a). This is expected to, according the United Nations, reach 70% by 2050 (UN 2015a). In the current climate of the unprecedented urbanization and increased uncertainty of the world, it is becoming increasingly more challenging for cities to configure themselves more sustainably from an environmental perspective. This in turn implies that the city governments in both the technologically and ecologically advanced nations will face significant challenges due to the issues engendered by urban growth, including increased energy consumption, environmental degradation, environmental pollution, inefficient management of infrastructures, ineffective planning strategies, inadequate decision–making systems, as well as socio-economic disparities and social inequalities (Bibri 2019a; Bibri and Krogstie 2017a). In particular, urban growth raises a variety of problems that jeopardize the environmental sustainability of cities as it puts an enormous strain on urban systems and thus great demand on energy resources and services. Energy as a key urban domain produces the largest share of the world's emissions of GHG. This makes it the dominant contributor to climate change, and increasing GHG emissions continue to drive climate change. With rising GHG emissions, climate change is occurring at rates much faster than anticipated and its effects are clearly felt worldwide (UN 2019a). The Sustainable Development Goal (SDG) 13 aims to take urgent actions to combat climate change and its impacts (UN 2019b). Nonetheless, modern cities play a leading role in strategic sustainable development and have a central position in developing and applying new technologies to support the transition towards sustainability in the face of urbanization.

For cities to disentangle the kind of wicked problems, intractable issues, and complex challenges related to climate change, they need to develop and apply more innovative solutions and sophisticated approaches enabled by cutting–edge technologies and underpinned by groundbreaking scientific knowledge. This is necessary to monitor, understand, analyze, and plan cities in ways that enhance, optimize, and maintain their performance with respect to environmental sustainability. In this respect, the United

Nation's 2030 Agenda regards advanced Information and Communication Technology (ICT) as a means to protect the environment, increase resource efficiency, achieve human progress and knowledge, and upgrade legacy infrastructure (UN 2015a). Therefore, the multifaceted potential of the smart city approach has been under investigation by the UN (2015b) through their study on "Big Data and the 2030 Agenda for Sustainable Development." This is of high importance and relevance to the SGD 7 of the UN's 2030 Agenda (UN 2015b): "ensure access to affordable, reliable, sustainable, and modern energy for all" (UN 2019a, b). Energy is at the core of sustainable development goals, and thus the modernization of energy systems is more needed than ever.

Currently, greater importance is given to economic development and social development at the cost of environmental integration and protection. In recent years, major topics discussed in this area have included the depletion of non-renewable resources, the harvesting of renewable resources, the destruction of ecosystems, and the generation of pollution. Therefore, advanced computational data analytics approaches are required to observe and discover hidden patterns of energy production and consumption in order to devise more effective solutions that could avert the multidimensional effects of devouring energy. There is a general consensus that innovative data-driven technology solutions hold great potential to improve energy efficiency and mitigate climate change. Indeed, advanced ICT is seen as a critical enabler for advancing environmental sustainability given its unique ability to make energy consumption and GHG emissions visible through its processes, products, and services. This is at the core of the vision of smart energy. This aims to achieve energy systems that are highly energy-efficient, increasingly powered by renewable and local energy sources enabled by new technologies, and less dependent on fossil fuels (Walnum et al. 2019). The vision has spurred the development of new approaches to future sustainable energy systems, such as smart grids, smart meters, green buildings, and solar photovoltaic panels (Lund et al. 2017; Koutitas 2018). The smart city discourse emphasizes the role and potential of advanced ICT as a distributed infrastructure of smart meters, computing resources, and interfaces together forming a sort of digital nervous system for the city in facilitating the management of urban infrastructures, systems, and services (Batty et al. 2012; Bibri 2019a, 2020a; Kitchin 2014; Townsend 2013).

It is clear that we can have a positive impact on the environment by making cities more sustainable in terms of their energy systems by means of modern technologies. In particular, recent advances in the IoT and big data analytics along with higher-level computational infrastructures have presented many new opportunities to develop applied solutions in the form of intelligence functions for energy efficiency and pollution reduction, notably within the framework of smart sustainable cities. This emerging global paradigm of urbanism is indeed seen today as the most important arena for sustainability transitions in an increasingly urbanized world. It holds great potential to instigate major societal transformation by linking together the agendas of sustainable development and technological innovation. Of particular relevance to this study, numerous alternative approaches based on the IoT and big data technologies have materialized in recent years, providing the raw material for both smart cities and sustainable cities to improve their environmental performance in the face of the escalating urbanisation trend.

Already, the number of objects connected to the Internet has, according to Cisco, exceeded the number of human beings in the world. And the increasing number of the networked devices deployed across urban environments has resulted in the exponential growth in the amount of data generated by sensors, thereby the relevance of big data analytics techniques for handling the storage, management, processing, and analysis of this magnitude of data. On the whole, the IoT and big data technologies are seen as the backbone for building smart sustainable cities of the future.

Big data technologies have become essential to the functioning of smart cities (e.g., Batty 2013; Khan et al. 2015; Kitchin 2014, 2015, 2016; Kitchin et al. 2015; Rathore et al. 2016, 2018; Townsend 2013), particularly in the endeavor to improve their performance with respect to environmental sustainability (e.g., Al Nuaimi et al. 2015; Angelidou et al. 2017; Batty et al. 2012; Bibri 2019c, 2020a; Bibri and Krogstie 2020b; Hashem et al. 2016; Kumar and Prakash 2016; Nikitin et al. 2016; Perera et al. 2017). The same applies to sustainable cities (e.g., Bibri 2018a, b, 2019a, b, 2020a, b; Bibri and Krogstie 2017b, 2019a, 2019b, 2020a, c; Kramers et al. 2014; Pasichnyi et al. 2019; Shahrokni et al. 2014b, 2015a, b; Sun and Du 2017). Consequently, urban processes and practices are becoming highly responsive to a form of data-driven urbanism that is increasingly becoming the key mode of operation and organization for smart sustainable cities. To put it differently, we are moving into an era where instrumentation, datafication, and computation are routinely pervading the very fabric of both smart cities and sustainable cities, coupled with the integration and coordination of their systems and domains. As a result, vast troves of data are being generated, analyzed, harnessed, and exploited to control, manage, and regulate various domains of city life. With these developments, smart sustainable cities are being increasingly designed in ways that allow to monitor, understand, analyze, and plan their systems and infrastructures in real time. This is changing the way cities can be planned across multiple time scales, raising the prospect that cities can be made smarter and more sustainable in the long term by continuous reflection in the short term.

In light of the above, advanced ICT, especially the IoT and big data technologies, constitutes a promising response to the challenges of environmental sustainability due to its tremendous, yet untapped, potential for tackling many problems associated with energy consumption and air and noise pollution. However, prior studies tend to deal largely with the IoT and big data technologies in the realm of smart cities (e.g., Ahmed et al. 2017; Berkel et al. 2018; Ji et al. 2014a, b; Kumar and Prakash 2016; Perera et al. 2014; Rathore et al. 2016, 2018; Wan et al. 2016; Zanella et al. 2014), mostly in relation to economic and social aspects (Ahvenniemi et al. 2017), leaving important questions involving the underlying substantive and synergistic effects on environmental sustainability barely explored to date. These issues also apply to sustainable cities, especially eco-cities (e.g., Bibri 2018b, 2019b, 2020a, b; Höjer and Wangel 2015; Kramers et al. 2014). In a nutshell, the integration of the IoT and big data technologies is an unexplored research area as regards the new opportunities it offers in terms of responding to the challenges of environmental sustainability.

With the above in regard, this paper investigates the potential and role of data-driven smart solutions in improving and advancing environmental sustainability in the context of smart cities as well as sustainable cities under what can be labeled "environmentally data-driven smart sustainable cities." Prior to this, it provides an overview of the state-of-the-art enabling technologies of the IoT and big data computing and the associated city infrastructures, frameworks, operating systems, and operations centers. The main motivation for this study is to invigorate the application demand for the solutions that the IoT and big data technologies can offer for environmental sustainability.

This paper unfolds as follows: Research methodology section details and justifies the research methodology adopted in this study. The key components of the IoT section provides an overview of the technical literature on the IoT and big data technologies in the context of smart cities and smart sustainable cities. Results section presents the results, which are, in Discussion section, discussed and interpreted in perspective of previous studies. Finally, this paper concludes, in Conclusion section, by drawing the main findings, providing some reflections, and suggesting some avenues for future research.

Research methodology

Case study research

Case study research has long had a prominent position in many disciplines and professional fields, established as a credible, valid design that facilitates the investigation and understanding of complex phenomena in their real-world settings. It has benefited from the prior development of the theoretical propositions contributed by a number of researchers with different backgrounds to this design. Similarly, the methodological development of case study research has emanated from the influence of the different researchers' perspectives and interpretations of this design. This has resulted in a pragmatic flexible research approach, capable of providing an up-close, in-depth, and detailed examination of a wide range of specific cases and a comprehensive understanding of a large number and variety of issues. Therefore, case study research has grown in reputation as an effective research methodology. As a result, it has undergone substantial improvement through the application of a diversity of approaches. Central to this is the underpinning ontological and epistemological orientations of the numerous researchers involved in the evolution of case study research as coming from various disciplines. While over time the contributions of those researchers have helped to develop and strengthen case study research, the variety of disciplinary backgrounds has also added complexity, particularly around how such research is defined, described, and applied in practice. The nature of this complexity is explored in more detail by Farquhar (2012).

Case study research: definition and context

There is a variety of definitions and descriptions of case study research presented across the literature, which has resulted from researchers with different philosophical perspectives. The proliferation of definitions can create confusion when attempting to understand case study research. The most common definitions come from the work of Yin (2014, 2017), Stake (1995), Merriam (2009), Thomas (2011), Simons (2009), and Creswell et al. (2007). As a working definition for this paper, Creswell et al. (2007) describe case study as a type of design in qualitative research, an object of study, and a product of the inquiry. The authors conclude with a definition that collates the hallmarks of the key approaches to case study and represents the core features of a case study: “a qualitative approach in which the investigator explores a bounded system (a case) … over time through detailed, in–depth data collection involving multiple sources of information … and reports a case description and case–based themes" (Creswell et al. 2007, p. 245). In particular, the case study approach entails the use of multiple sources of evidence. The use of multiple methods to collect and analyze data are found to be mutually informative in the case study research where together they provide a more synergistic and comprehensive view of the problem under study (Flyvbjerg 2011; Merriam 2009; Stake 2006; Stewart 2014).

Against the backdrop of this paper, this case study analyzes a range of different elements within the boundaries of two cities. It examines a contemporary real-world phenomenon and seeks to inform the theory and practice of data-driven smart sustainable urbanism by illustrating what has worked well, what has been achieved, what is the current situation, what needs to be improved in the future, and how this can be done. It serves as a way to illustrate theories and the effects of their application in regard to urban living. It is additionally regarded useful for understanding how different elements fit together and (co-)produce the observed impacts in a particular context based on a given set of intertwined factors.

Case study design, purpose, and process

Various designs have been proposed for preparing, planning, and conducting case study research. The philosophical underpinnings of the researchers that have contributed to the development of case study research have created a variety and diversity of approaches. Under the more generalized category of case study, there exist several categories, each of which is custom selected for use depending on the objectives of the researcher, including:

- Illustrative case studies—these are primarily descriptive studies.
- Exploratory case studies—these are condensed case studies performed before implementing a large scale investigation.
- Cumulative case studies—these serve to aggregate information from several sites collected at different times.
- Critical instance case studies—these examine one or more sites either for the purpose of calling into question a highly generalized or universal assertion.

According to this classification, this case study is illustrative in design. Illustrative case studies, which are primarily descriptive in nature, typically utilize one or two instances of an event to show the existing situation. They serve primarily to make the unfamiliar familiar and to give readers a common language about the topic in question.

The methodological discourse stresses a number of themes on the direction and organization of case studies—their design. Thomas (2011) summarizes some of the better-known analyses in Table 1.

For an explication of the general themes raised in Table 3, the interested reader can be directed to the analysis from George and Bennett (2005). Furthermore, while case study research has evolved to be a pragmatic, flexible research approach, the variation in application, purposefulness, and validity can create a confusing platform for its use (Anthony and Jack 2009). Nevertheless, the versatility of case study research to

Table 1 Kinds of case studies as enumerated by different analysts

George and Bennett (2005, drawing on Eckstein, 1975)	Merriam (1988)	Stake (1995)	Bassey (1999)	de Vaus (2001)	Mitchell (2006) (drawing on Eckstein, 1975)	Yin (2009)
Theory testing	Descriptive	Intrinsic	Theory seeking	Descriptive/ explanatory	Illustrative	Critical
Atheoretical/ configurative-idiographic	Interpretative	Instrumental	Theory testing	Theory testing/ theory building	Social analytic	Extreme/ unique
Disciplined configurative	Evaluative	Single/ collective	Storytelling	Single/multiple case	Extended (over time)	Longitudinal
Heuristic	—	—	Picture drawing	Holistic/embedded	Configurative-idiographic	Representative
Plausibility probes	—	—	Evaluative	Parallel/sequential	Disciplined-configurative	Revelatory
"Building block" studies	—	—	—	Retrospective/ prospective	Heuristic	—
					Plausibility probes	

Source: Thomas (2011)

accommodate the researcher's position presents a unique platform for a range of studies that can generate greater insights into different areas of inquiry. With the capacity to tailor approaches, case study designs can address a wide range of questions that ask why, what, and how of an issue and assist researchers to explore, explain, describe, evaluate, and theorize about complex issues in context. This pertains to the decisions that need to be made about the purpose, approach, and process in the case study. Thomas (2011) proposes a typology for the case study wherein purposes are first identified (evaluative, exploratory, or descriptive), then approaches are delineated (theory-testing, theory-building, or illustrative), then processes are decided upon, with a principal choice being between whether the study is to be single or multiple, among other things.

Following this typology, the purpose in this case study is *descriptive*, the approach is *illustrative*, and the process is *multiple*. The purpose is about the reason of doing this study. The approach is about the broad object of this study. The process is bout the operational processes of this study, which entails returning to the two subjects (as distinct from the object) in question and to the boundary decisions made at the outset. There has to be an examination of the nature of the decisions that are made at that time about the parameters that delimit the subject of the study (Thomas 2011). In this context, these parameters fall around the locus of defining the two cases by more of a range of boundary considerations: a range of different elements that were studied in their complexity. This determines the process of the case study, and this is about the presence of the comparative element to this study as consisting of two instances (Stake 2005). As stated by Thomas (2011, p. 517): "the case study, while it is of the singular, may contain more than one element in its subject and if this is so—that is, if there are two or several cases—each individual case is less important in itself than the comparison that each offers with the others." The key focus in this case study is not on the nature and shape of relationships per se in one city but rather on, to some extent, the nature of the difference between the one and the other and what this informs us about the dynamics that are significant in this difference. This comparative element is why Schwandt (2001) calls this kind of case study cross-case analysis.

To elaborate further on the purpose, descriptive case study accentuates the flexibility of case study research as a distinct form of inquiry that enables detailed and in-depth insights into a diverse range of issues across a number of disciplines. There is a consensus that the focus of a case study is the detailed inquiry of a unit of analysis as a bounded system (the case), over time, within its context. In descriptive case study research, questions and propositions about the phenomenon under study are carefully scrutinized and articulated at the outset. The articulation of what is known about this phenomena is referred to as a descriptive theory. Therefore, the primary purpose of this case study is to describe the selected cases in detail and in depth based on that articulation, and in their real–world settings. It is worth pointing out that internal validity in research design is not relevant as in most descriptive studies. Internal validity denotes the approximate truth about inferences regarding cause-effect, or the extent to which a study establishes a trustworthy cause-and-effect relationship between a treatment and an outcome. Accordingly, it is relevant in studies that attempt to establish a causal relationship, such as explanatory and hypothesis-generating (or heuristic) case studies, whereas descriptive research is used to describe some characteristics of certain phenomena, and does not address questions about why and when these characteristics occurred—no causal relationship (Bibri 2020a).

Descriptive case study steps

Descriptive case study research, as defined by (Yin 1984, 2009), has been identified as the most suitable methodology for this study. This methodology has been chosen considering the nature of the problem being investigated, the research aim, and the present state of knowledge with respect to the topic on focus. It involves the description, analysis, and interpretation of the present nature, composition, and processes of the two cities selected, where the focus is on the prevailing conditions. That is, how these cities behave in terms of what has been realized and the ongoing implementation of plans based on the corresponding practices and strategies related to environmental sustainability. To obtain a broad and detailed form of knowledge in this regard, we adopted a process that consists of the following steps:

- Using a narrative framework that focuses on data-driven smart solutions and their role and potential in improving and advancing environmental sustainability in the framework of the smart sustainable city as a real–world problem, and provides essential facts about it, including relevant background information.
- Introducing the reader to key concepts, core enabling technologies, infrastructures, landscapes, frameworks, as well as operating systems and urban operations centers, all with relevance to the problem under study.
- Identifying the commonalities and differences between the two cities with respect to the emerging n technologies
- Explaining the actual solutions in terms of plans and visions, the processes of implementing them, and the realized and expected outcomes
- Offering an analysis and evaluation of the relevant solutions and related issues, including strengths, weaknesses, and lessons learned.

Selection criteria

According to Seawright and Gerring (2020), there are different strategics for selecting the cases to be investigated, namely typical cases, diverse cases, extreme cases, deviant cases, influential cases, cost similar cases, and most different cases. The strategy adopted in this study is *influential cases*—which are central to a model or theory. The subjects have come into focus because of the inherent interest of the two cases—they are key cases of the phenomenon of environmentally data-driven smart sustainable cities. However, the subjects identified are in no sense a sample, representative of a wider population. Rather, they are selected because they are interesting examples through which the lineaments of the object can be refracted. Their scope is not restricted (e.g., Thomas 2011; White 1992).

The cases of Stockholm and Barcelona were selected using a theoretical sampling approach (Yin 1984, 2009). The Cities of Stockholm and Barcelona fall within the category of large cities in Europe. The area of Stockholm has an approximate size of 188 km and a population of 1,632,798 million habitants, and the area of Barcelona has an approximate size of 101.9 km^2 and a population of 5.586 million habitants. Additionally, the success of the two cities in the field of sustainable urbanism and smart urbanism, respectively, makes their strategies and solutions an ideal sample to analyze. This assertion can be easily demonstrated considering the multiple awards the two cities have received during recent years and their international positioning. The latter pertains to Stockholm as both a sustainable city and a smart sustainable city (e.g., Akande et al. 2018; Bibri 2020a, b; Bibri and Krogstie 2020a; Holmstedt et al. 2017; Kramers et al. 2016, Stockholm City 2009, 2010, 2018, 2020). And it relates to Barcelona as a smart city (e.g., Achaerandio et al. 2011; Ajuntament de Barcelona 2014a; Cohen 2012a, b, 2014; European Commission 2014; Eden Strategy Institute 2018; Manville et al. 2014; Nikitin et al. 2016) and a sustainable smart city (e.g., Bibri and Krogstie 2020b; Noori et al. 2020). Indeed, Barcelona is taking concrete actions for implementing the applied data-driven technology solutions developed for urban operational functioning and planning as part of the city management to improve and advance sustainability—thereby evolving into what has been termed as a data-driven sustainable smart city (Bibri 2020a). Barcelona is strongly committed to becoming a smart city and a show-case for the rest of the world in sustainable urban development (Mora and Bolici 2016). This is clearly figured in the public statements proposed by different local government representatives (see, e.g., Ajuntament de Barcelona 2011, 2012c, 2013, 2014b, c).

In view of the above, the two cities demonstrate exemplary practical initiatives as regards the integration of data-driven solutions and sustainable development strategies. As such, they may be seen as successful examples of the environmentally data-driven smart sustainable city, as well as critical cases in environmental sustainability. This is further due to the national focus on environmental sustainability in Stockholm and the national focus on ICT in Barcelona, with visible shared goals and visions in regard to these foci. All in all, the selection secured cases where advances in the IoT and big data technologies and their novel applications for environmental sustainability, coupled with future visions and goals, are present.

Subject, object, unit of analysis, and data collection

Whatever the frame of reference for the choice of the subject of the case study, there is a distinction to be made between the subject and the object of the case study. The subject is the "practical, historical unity" through which the theoretical focus of the study is being viewed (Wieviorka 1992), and the object is the analytical frame within which the study is conducted and which the case illuminates (Thomas 2011). Environmentally data-driven smart sustainable urbanism was identified as the universe—that is, the class of events—of which a group of two cases in this study represent instances. The subjects of this case study, which are the two cases themselves, are thus the instances of this urban phenomena, and the latter—the phenomena—comprise the analytical frame.

For a "case" to exist, we must be able to identify a characteristic unit … This unit must be observed, but it has no meaning in itself. It is significant only if an observer … can refer it to an analytical category or theory. It does not suffice to observe a social phenomenon, historical event, or set of behaviors in order to declare them to be "cases." If you want to talk about a "case," you also need the means of interpreting it or placing it in a context (Wieviorka, 1992, p. 160). The unit of analysis is the data-driven solutions applied in the sustainable city and the smart city for environmental sustainability.

The unit of analysis is essential to focalizing, framing, and managing the data collection and analysis. The qualitative data were extracted from multiple sources of evidence identified with a series of searches performed in various online databases. The relevant archive records and documents produced by public and private organizations were considered as primary sources (i.e., master plans, comprehensive plans, visions, strategies, agendas, project descriptions, presentations, interviews, etc.). In addition, a wealth of information was acquired from other documents produced by organizations or researchers not directly involved in the initiatives of the city cases. These sources were considered as secondary (i.e., reports, newspaper articles, journal and online articles, conference proceedings, research project deliverables, etc.).

Data analysis approach

To identify, analyze, interpret, and report the case–based themes, a thematic analysis approach was designed and employed. This qualitative analytical approach was deemed suitable given the form of knowledge and insights that we sought to gain from the qualitative data gathered in connection with the case study. Generally, it is up to the researcher to decide if this analytical approach is suitable for their research design, and whether it can be adapted for their own uses or purposes. However, thematic analysis is particularly, albeit not exclusively, associated with the analysis of textual material. Also, it is more appropriate when dealing with a large body of qualitative data. It emphasizes identifying, analyzing, interpreting, and reporting themes, i.e., important patterns of meaning within the qualitative data that can be used to address the research problem. Braun and Clarke (2006) suggest that thematic analysis is flexible in terms of research design given that it is not dependent on any particular theory: multiple theories can be applied to this process across a variety of epistemologies. Furthermore, thematic analysis is an umbrella term for a variety of different approaches, which are divergent in regard to procedures. In this study, we adopted an inductive approach to thematic analysis, which allows the data to determine the set of themes that are to be identified. That is to say, we developed our own framework based on what we found as themes (inductive) by discovering patterns, themes, and concepts in the collected data. For a detailed discussion of thematic analysis as a qualitative method, the interested reader can be directed to (Bibri 2020a).

The main steps of the analytical approach are as follows:

1. Reviewing the multiple sources of the data related to the selected cases. The outcomes of this process are numerous themes that are associated with the model of urbanism in question. This step provides the foundation for the subsequent analysis.
2. Pattern recognition (searching for themes) entails the ability to see patterns in seemingly random information. The aim is to note major patterns within the result of the first step. The second step looks for similarities within the sample and codes the results by concepts. In this step, the preliminary codes identified are the features of data that appear meaningful and interesting, and the relevant data extracts are sorted according to the overarching themes.
3. Revising themes is about combining, separating, refining, or discarding initial themes. This relates mainly to the inductive approach to thematic analysis. Data within the themes should cohere together meaningfully and be clear and identifiable as regards the distinction between these themes. A thematic 'map' is generated from this step.
4. Producing the report involves transforming the analysis into an interpretable piece of writing by using vivid and compelling data extracts that relate to the overarching themes, research questions, and literature. This is a fundamental step for supporting future comparative research and cross-case analysis (Yin 1984; Patton 2012). The report must portray an analysis supported with the empirical evidence that addresses the research problem.

This analytical strategy has allowed us to analyze the selected cases considering the different perspectives of multiple observers. Moreover, the final description of the process has gained greater strength thanks to the triangulation made possible by the use of multiple sources of evidence (George and Bennett 2005; Yin 1984; Voss et al. 2002).

The key components of the IoT

The IoT and big data technologies and their relationship

In recent years, the IoT and big data analytics has become the predominant paradigm of urban computing. Using today's large-scale computing infrastructure and data gathered from sensing technologies via mainly wireless networks, this paradigm integrates computer science, data science, complexity science, urban science, data-intensive science, urban planning, urban sustainability, environmental science, sociology, and so forth, tackling a plethora of specific problems with concrete (scientific and computational) methodologies and simulation and modelling approaches in a data-centric computing framework.

The IoT has become a key component of the ICT infrastructure of smart sustainable cities. According to Giusto et al. (2010), the IoT is a "communication paradigm which visualizes a near future, in which physical objects are equipped with micro–controllers, transceivers for digital communication and fitting protocol stacks that will make these objects able to communicate with each other and with the users." Bibri (2020a) defines the IoT as the interconnection of uniquely identifiable embedded devices and smart objects connected to humans, embedded in their environments, and spread along the trajectories they follow using the Internet Protocol version 6 (IPv6), embedded systems, intelligent entities, and communication and sensing–actuation capabilities. The connectivity achieved by the IoT encompasses people, machines, tools, and places located anywhere. From a functional perspective, the IoT is defined as the IoT "allows people and things to be connected Anytime, Anyplace, with Anything and Anyone, ideally using Any path/network and Any service" (European Commission 2008, cited in Perera et al. 2017). The IoT is evolving into even more sophisticated network of sensors and physical objects, spanning all kinds of everyday objects. Looking to the future, a new forecast from International Data Corporation (IDC) estimates that there will be 41.6 billion connected IoT devices, or "things," generating 79.4 zettabytes (ZB) of data in 2025. Cisco IBSG predicts there will be 50 billion by 2020. As the number of connected IoT devices grows, the amount of data generated by these devices will also grow. It is important to note that these estimates do not take into account rapid advances in Internet or device technology; the numbers presented are based on extrapolation in terms of assuming that the existing trend will continue, or on what is known to be true today.

The IoT is viewed as part of the Internet of the future, which is expected to be dramatically different from what has hitherto been experienced in terms of the use of the Internet as we know today. The use of the IoT is intended "to achieve different intelligent functions from information exchange and communication, including learning about things, identifying things, tracking and tracing things, connecting with things, searching for things, monitoring things, controlling things, evaluating things, managing things, operating things, repairing things, and planning things" (Bibri 2018b, p. 8). In short, the objective of the IoT is to enable communications with and among smart objects as well as with people and their environment, without any human intervention. Zanella et al. (2014) state that the intention of the IoT is to make the Internet even more engaging and omnipresent by allowing easy entrance and communication with a large variety of devices so that it can support the development of a number of applications which make use of the possibly gigantic bulk and diversity of data produced by objects to present new services to citizens, companies and public administrations. This involves the value that is to be extracted from large masses of urban data for enhanced decision making and deep insights pertaining to a wide variety of practical uses and applications in relation to environmental sustainability. This is associated with smart cities (e.g., Al Nuaimi et al. 2015; Angelidou et al. 2017; Batty et al. 2012; Hashem et al. 2016), data-driven smart cities (e.g., Bibri and Krogstie 2020b; Nikitin et al. 2016), and smart sustainable cities (Bibri 2018b, 2019b, 2020a). The IoT–based infrastructure will allow different classes of cities to devise solutions for solving many environmental problems in a more efficient, effective, and responsible way. The upcoming data avalanche is the primary fuel of this new age where powerful computational processes use this fuel to create more sustainable, efficient, and resilient cities (Bibri 2019d).

There is no agreed academic or industry definition of big data. Therefore, many definitions have been suggested and are available in the literature, with each tending to offer a particular or different view of the concept based on the context of use. Many surveys of the emerging literature denote a number of key characteristic features of big data and tend to converge on three main attributes: the huge volume of data, the wide variety of data types, and the velocity at which the data can be collected and processed, more specifically:

Volume: This relates to the size of the data such as terabytes, petabytes, zettabytes, and so on.
Variety: Different sources can produce data such as sensors, devices, websites, LIDAR (Light Detection and Ranging), and smartphones, resulting in such types of data as RFID and GPS sensor readings, web logs, 3-D representations, and streamed video and audio.
Velocity: This means how frequently the data is generated in terms of time scale. Moreover, some data need to be processed in real-time and other data may only be processed when needed. Typically, three main categories can be identified, namely real-time, frequent, and occasional.

Generally, the term "big data" is essentially used to mean collections of datasets whose attributes make it extremely difficult to manage, process, and analyze using the traditional database systems and software techniques. In the context of smart sustainable cities, the concept of big data can be used to describe a colossal amount of urban data, typically to the extent that their manipulation, analysis, management, and communication present significant computational, analytical, logistical, integrative, and coordinative challenges. Kitchin (2014, p. 3) describes big data as:

- huge in *volume*, consisting of terabytes or petabytes of data;
- high in velocity, being created and used in or near real–time;
- diverse in *variety*, being a mix of structured and unstructured data, and often being temporally and spatially referenced;
- *exhaustive* in scope, striving to capture entire populations or systems (n = all), or at least much larger sample sizes than would be employed in traditional, small data studies;
- fine–grained in *resolution*, aiming to be as detailed as possible, and uniquely indexical in identification;
- *relational* in nature, containing common fields that enable the conjoining of different data sets;
- *flexible*, holding the traits of extensionality (can add new fields easily) and scaleability (can expand in size rapidly).

The term "big data analytics" refers to a type of quantitative research that examines large amounts of data to uncover hidden patterns, unknown correlations and other useful information. In more detail, this term denotes any vast amount of data that has the potential to be collected, stored, retrieved, integrated, selected, preprocessed, transformed, analyzed, and interpreted for discovering new or extracting useful knowledge. The obtained results can be evaluated and visualized in an understandable format before their deployment for decision–making purposes (e.g., improving, adjusting, or changing an operation, function, service, strategy, or policy). In the framework of smart sustainable cities, big data analytics refers to a collection of sophisticated and dedicated software applications and database management systems run by machines with very high processing power, which can turn a large amount of urban data into useful knowledge for enhanced decision–making in relation to various urban systems and domains, such as energy, environment, and transport.

A great deal of the unfolding big data deluge is due to the IoT as a form of ubiquitous computing. The IoT and big data are massive, complex ideas. While interrelated, they are also recognizably different in nature. The IoT consists of millions of networked devices that collect, transfer, and communicate information, but big data encompasses a much wider landscape. The enormous collection of connected sensors, devices, and other "things" that represent the IoT is making a significant contribution to the volume and variety of the data being generated. The IoT and big data remain distinct but complementary. While both the IoT and big data denote collecting large sets of data, only the IoT seeks to run analytics simultaneously to support real-time decisions (e.g., in city operations centers). While the focus of IoT is more on the immediate analysis and use of incoming data, big data tools can still aid some functions. Types of data sources are another major distinction between the two. Big data analytics typically looks at human choices in an effort to predict behavior and uncover patterns or shifts. On the other hand, the IoT is centered on machine-generated data, and its primary goals are machine-oriented—optimal system performance (e.g., smart grids, smart appliances, street lighting, etc.), predictive maintenance, and so on. The IoT and big data emphasize the need for converting data into tangible insights that can be acted upon. They have an important relationship that will continue to develop in parallel with new advances in technology. Cities wishing to harness the power of data should carefully consider the devices they choose to deploy and the types of information they collect. Making an effort at the front end to gather only useful, actionable data—and designing internal systems to process these in domain-specific ways—will make the process of analytics that much easier. To gain further insights into the relationship between the IoT and big data analytics, the interested reader can be directed to Bibri (2018b).

Sensors and things

The IoT involves a myriad of sensors and deals with numerous physical and virtual objects due to the scale of its ubiquity and the huge range of the applications it offers. As a form of countless wirelessly interconnected sensing and computing devices, the IoT is increasingly pervading urban environments and making everyday objects smart by enabling them to communicate with each other, interact with people and their objects, and explore their surroundings. Hence, it entails a complex sensor infrastructure and processing platform, and thus requires innovative tools, processes, methods, and techniques to handle the volume, variety, and velocity of the colossal amount of data generated on a daily basis to enable new applications and services. Despite the difficulty in overcoming the hurdles to the wide adoption of the IoT within smart sustainable cities, the IoT has demonstrated distinguished potential to add a whole new dimension to environmental sustainability by enabling communication between and information exchange among the physical and virtual objects deployed across urban environments in connection with energy systems and services.

Sensor technology is the key enabling technology of the IoT. The sensors serve as main sources for big data analytics as a computational process. In this respect, the automated approach to data generation is the most common and prominent in the context of the IoT. There are a number of tools associated mainly with sensors that can be employed in the automated approach to generating urban data (Batty et al. 2012; Bibri 2018b, 2020a; Dodge and Kitchin 2007; Kitchin 2014; Kitchin and Dodge 2011), including:

- GPS in vehicles and on people
- Smart tickets that are used to trace passenger travel
- RFID tags attached to objects and people
- Sensed data generated by a variety of sensors and actuators embedded into the objects or environments that regularly communicate their measurements
- Capture systems in which the means of performing tasks captures data about those tasks
- Digital devices that record and communicate the history of their own use
- Digital traces left through purchase of goods and related demand supply situations
- Transactions and interactions across digital networks that not only transfer information, but also generate data about the transactions and interactions themselves
- Clickstream data that record how people navigate through websites or apps
- Automatic meter reading (AMR) that communicates utility usage on a continuous basis
- Automated monitoring of public services provision
- The scanning of machine–readable objects such as travel passes, passports, or barcodes on parcels that register payment and movement through a system
- Machine to machine interactions across the IoT
- Uniquely indexical objects and machines that conduct automatic work as part of the IoT, communicating about their use and traceability if they are mobile (automatic doors, lighting and heating systems, washing machines, security alarms, wifi router boxes, etc.)
- Transponders that monitor throughput at toll–booths, measuring vehicle flow along a road or the number of empty spaces in a car park, and track the progress of buses and trains along a route.

In the domain of urbanism, these categories of digital instrumentation provide abundant, systematic, dynamic, varied, well–defined, resolute, relatively cheap data about urban processes and activities, allowing for real–time analytics and adaptive forms of planning and management (Bibri 2020a). They can continually send data to an array of control and management systems that can process and respond in real time to the data flow.

However, the various sensor recording parameters, their length as to the collected data, where they are located, what kinds of sensors are embedded in which environments, their settings and calibration, their integration and fusion, and their exhaustiveness as technical configurations and deployments all determine the nature of the data to be generated and the way they are stored, managed, processed, analyzed, and disciplined. Regardless, the trend of embedding more and more of the IoT sensors into smart sustainable cities will undoubtedly continue and even escalate for the purpose of providing the most suitable tools for measuring urban parameters and new techniques and platforms for data processing and analytics. Especially, this form of ICT of pervasive computing has an instrumental and shaping role in not only monitoring, understanding, and analyzing smart sustainable cities, but also in improving sustainability, efficiency, resilience, and the quality of life of their citizens.

The automated approach is associated with various automatic functions of the devices and systems that are widely deployed across urban environments. Therefore, it has recently captured the imagination of those concerned with understanding, operating, managing, and planning urban systems, in particular in relation to environmental sustainability, especially within the framework of the IoT. Purposely sensed data reflect the power of ubiquitous sensors that can be deployed ad hoc in public and private spaces to better understand some aspects of urbanity and urban dynamics. Indeed, there has been increased interest in the IoT and especially its sensor network with respect to monitoring the operation and condition of urban and public infrastructure, such as energy systems, power grid systems, and environmental and green conditions.

By its nature, the IoT involves different types of things (Bibri 2020a):

- Tagging things, i.e., radio frequency identification (RFID) and near field communication (NFC) tags are attached to everyday objects and people
- Sensing things, i.e., sensors act as devices to collect the data from the physical world and transmit them to the virtual world
- Thinking things, i.e., smart things process information, make independent decisions, self–configure, self–regulate, and self–repair
- Miniaturized things, i.e., sensing and computing devices based on micro–electro–mechanical systems (MMES) or nano–electro–mechanical systems (NMES). These are so small to be virtually invisible, embedded in everyday objects to enable them to interact and connect within the smart things thanks to micro–engineering and nanotechnology.

The IoT involves all kinds of objects, including individuals, road traffic, parking, public transit, street lighting, buildings, water systems, energy systems, distribution networks, vehicles, appliances, and air. These objects entail devices with intelligence, communication, sensory, and actuation capabilities related to such applications as machine–to–machine, vehicle–to–vehicle, and people–to–things applications. In short, the IoT encompasses sensor and actuator technologies, wireless technologies, and smart things.

Big data analytics for the IoT

Big data analytics as a holistic system

The pursuit of mastering the complexity of the data mining (also referred to as knowledge discovery) process for smart sustainable cities on the basis of the IoT requires building an entirely new holistic system for big data analytics based on linking the built environment (including, forms, energy system, water system, waste system, etc.) and the infrastructure passing into and out of urban areas (i.e. transportation systems, communication systems, and distribution networks) to its operational functioning, management, and planning. This is necessary for facilitating the implementation of urban intelligence and planning functions directed towards advancing and maintaining the contribution of smart sustainable cities to environmental sustainability through continuously optimizing and enhancing the operations, functions, services, designs, strategies, and policies associated with energy as an urban system and domain.

The entire analytical process able to create the needed knowledge services for enhanced decision–making and deep insights should be expressible within systems which support the following (Bibri 2020a; Bibri and Krogstie 2020c):

- The acquisition of data from multiple distributed sources, mainly automatically and routinely sensed data
- The management of data streams
- The integration of heterogeneous data into a coherent database
- The transformation and preparation of data
- The distribution of data mining and network analytics
- The organization of the extracted models and patterns
- The formation of patterns and models
- The evaluation of the quality of the extracted models and patterns
- The visualization and exploration of the behavioral patterns and models
- The building of simulation and prediction methods on top of the mined patterns and models
- The deployment of the obtained results for intelligent decision supports

Accordingly, the urban data are processed using various analytic tools (see, e.g., Bibri and Krogstie 2017c; Yaqoob et al. 2016). Figure 1 illustrates the process of data collection, monitoring, and analytics in the IoT within smart cities.

The core enabling technologies of ubiquitous computing and the big data ecosystem

Big data trends are associated with the IoT as a form of ubiquitous computing, which involves myriads of networked sensors that pervade urban environments on a massive scale. Accordingly, the nature of data generated is very complex and intricate, so is the big data ecosystem, a collection of infrastructure and tools, specialized analytics techniques, and applications used to capture, process, analyze, and visualize data. The soaring amount of urban data is due to a number of the core enabling technologies of ICT of ubiquitous computing (e.g., the IoT). These are being fast embedded into the very fabric of those cities that are badging or regenerating themselves as smart sustainable,

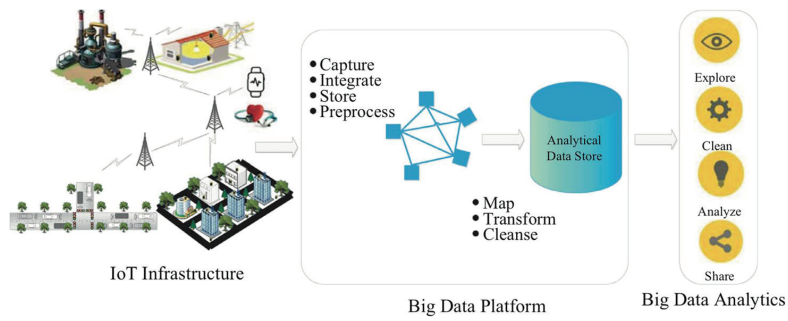

Fig. 1 Big data flow in the IoT within smart cities. Source: Ahmed et al. (2017)

whether smart cities or sustainable cities, to pave the way for adopting the upcoming innovative solutions to overcome the challenges of sustainability in the years ahead (Bibri 2019c). Furthermore, as with many domains to which big data analytics can be applied, smart sustainable cities require the big data ecosystem to be put in place as part of their ICT architecture in terms of the underlying core enabling technologies prior to adopting the kind of data-driven decisions and applications that support the goals of sustainable development, e.g., SDG 7. As a scientific and technological area, the core enabling technologies underlying the functioning of big data ecosystem associated with the IoT are under vigorous investigation in both academic circles and the ICT industry towards the development of digitally instrumented and computationally augmented urban environments that constitute the informational landscape of the emerging data-driven smart sustainable city (Bibri 2020a).

Generally, the big data ecosystem involves multivarious technologies in terms of quality and form, which allow to draw meaningful insights out of the large masses of available urban data. In the sphere of smart sustainable cities, the big data landscape is daunting, and there obviously is no one big data ecosystem or single go–to solution. There are a number of permutations of the core enabling technologies of ICT of pervasive computing (Bibri 2015a, b), which tend to be, in the context of big data analytics, shaped by the scale and complexity of the applied solutions developed and implemented in city domains. Bibri and Krogstie (2017c) provide a comprehensive state–of–the–art review of the core enabling technologies of big data analytics in relation to smart sustainable cities, including a synthesis of the key computational and analytical techniques, processes, and models associated with the functioning of the big data ecosystem. The components addressed by the authors in rather more detail include, but are not limited to:

- Pervasive sensing in terms of collecting and measuring urban data
- Data processing platforms
- Advanced techniques and algorithms
- Cloud and fog/edge computing models
- Smart network infrastructure
- Wireless communication networks

While there are some permutations that may apply to most city systems, there are some technical aspects and details that remain specific to smart sustainable cities. Regardless, it is necessary to take into account flexible design, quick deployment, extensible implementation, comprehensive interconnections, and advanced intelligence. Moreover, most of the permutations involve sensing technologies, data processing platforms, computing infrastructures, and wireless communication and networking technologies. These are intended to provide a full analytic system of big data analytics and its functional applications based on advanced decision support systems—e.g. urban intelligence functions and the associated simulations models and optimization and prediction methods. On this note, Batty et al. (2012) state that much of the focus on smart cities of the future, "will be in evolving new models of the city in its various domains that pertain to new kinds of data and movements and actions that are largely operated over digital networks … Very clear conceptions of how these models might be used to inform planning at different scales and very different time periods are critical to this focus … Quite new forms of integrated and coordinated decision support systems will be forthcoming from research on smart cities of the future."

Big data analytics solutions

There are different taxonomies of big data analytics in terms of the underlying components for the IoT. Ahmed et al. (2017) provide a thematic taxonomy of big data analytics solutions designed for the IoT systems (see Fig. 2). These solutions are categorized based on five attributes, namely big data sources, system components, big data enabling technologies, functional elements, and analytics types.

The common types of big data analytics (in addition to diagnostic) associated with the domain of smart sustainable urbanism are applied to generate a number of new urban intelligence functions, which are intended to be woven into the

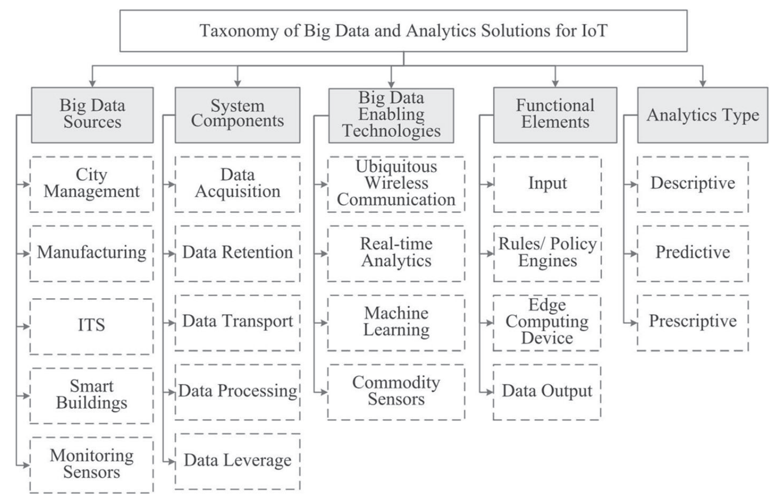

Fig. 2 A taxonomy of big data analytics solutions for the IoT systems. Source: Ahmed et al. (2017)

fabric of existing civic institutions whose mandate is advancing sustainability, optimizing efficiency, strengthening resilience, and enhancing the quality of life for citizenry (Bibri 2020a).

Cloud computing for the IoT and big data analytics

The fundamental objective of the IoT is to obtain and analyze data from physical assets or things that were previously disconnected from most data processing platforms. The IoT is about connecting the unconnected devices and things and sending the collected data from these connected objects to the cloud. In the IoT cloud architecture, all these data are transferred to the cloud for storage and computation. Thus, the IoT can be seen as a vast network of Cloud connected devices generating colossal amounts of data to be stored, processed, and analyzed. Big data are usually discussed with respect to cloud computing due to the fact that the latter theoretically provides infinite amounts of storage and computational resources. It is said that the Cloud has been one of the biggest disruptions of big data by separating storage and computation, by making it easy to scale and tune servers, and by bringing huge cost savings in processing data engineering pipelines at scale. Cloud computing denotes a computing model in which standardized, scalable, and flexible ICT–enabled capabilities are delivered in real–time over the cloud to external users via the Internet in the form of three types of services: (1) Software–as–a–Service (SaaS), (2) Platform–as–a–Service (PaaS), and (3) Infrastructure–as–a–Service (IaaS). SaaS denotes the provider's software applications, PaaS entails the provider's software development platforms, and IaaS means virtual servers, storage facilities, processors, and networks as resources. Therefore, cloud computing consists of several components, which can be rapidly provisioned with minimal management effort. Having attracted attention and gained popularity worldwide, cloud computing is becoming increasingly a key component of the ICT infrastructure of both smart cities and sustainable cities as an extension of distributed and grid computing due to the prevalence of sensor technologies, data processing platforms, pervasive computing infrastructures, and wireless communication networks. Especially, these core enabling technologies of ubiquitous computing have become technically mature and financially affordable by cloud providers. By commoditizing services, coupled with low cost open source software and geographic distribution, cloud computing is becoming increasingly an attractive option in the realm of smart cities and sustainable cities.

Cloud computing is increasingly seen as the most suitable solution for highly resource intensive and collaborative applications as an on–demand network access to a shared pool of computing resources (memory capacity, energy, computational power, network bandwidth, interactivity, etc.). This implies that computer–processing resources, which reside in the cloud, are virtualized and dynamic, and that only display devices for information and services need to be physically present with respect to various urban domains where many diverse actors from the different city departments can make use of software applications and services for the purpose of optimizing and enhancing urban operations, functions, designs, and strategies in line with the fundamental goals of sustainable development. Moreover, cloud computing performs service–oriented computing. As such, it can rapidly process large and complex data produced from urban activities and simultaneously serve citizens, e.g., utilities, providing a kind of an integrated and specialized center for information services to the general public. With reference to smart sustainable cities, cloud computing has the ability to run smart applications on many connected computers and smartphones at the same time in connection with sustainability, efficiency, and the quality of life (Bibri 2020a).

Overall, the key advantages provided by cloud computing include cost reduction, location and device independence, virtualization, scalability, performance, reliability, maintenance, as well as multi–tenancy (sharing of costs across a large pool of cloud provider's clients). Therefore, opting for cloud computing to perform big data analytics in the realm of smart sustainable cities (see Bibri 2018a, b for illustrative examples of the application of cloud computing in this regard) remains thus far the most suitable option for the operation of infrastructures, applications, and services whose functioning is dependent upon to what extent urban systems are integrated, urban domains are coordinated, urban networks are coupled, and whether they are scalable as to maximizing the benefits of sustainability.

Big data analytics can be performed in the Cloud. This involves both big data Platform as a Service (PaaS) and Infrastructure as a Service (IaaS). In line with the definition of cloud computing, there are three main elements of big data cloud (see Fig. 3).

Konugurthi et al. (2016) describe these three components in more detail. A summary of this description is presented below:

1. Big Data Infrastructure Services (BDIS): This layer offers core services, such as compute, storage, and data services for big data computing, namely basic storage

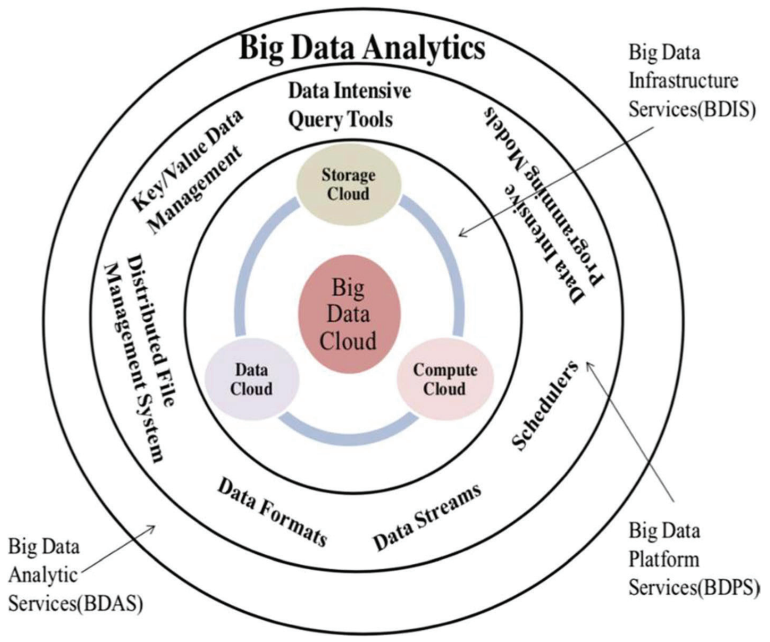

Fig. 3 Big data cloud components. Konugurthi et al. (2016)

service, data organization and access service, and processing service. The elements of BDIS are: computing clouds, storage clouds, and data clouds.

2. Big Data Platform Services (BDPS): This layer offers schedulers, query mechanisms for data retrieval, and data–intensive programming models to address several big data analytic problems.
3. Big Data Analytics Services (BDAS): This layer offers big data analytics as a set of services over big data–cloud infrastructure.

Using a thematic analysis, Bibri (2020a) offers an integrated framework for data-driven smart sustainable cities (see Fig. 4), which is intended to illustrate how the informational landscape of smart cities as based on the IoT and big data technologies could augment the physical landscape of sustainable cities in ways that can enhance their performance on the basis of data-driven smart applications. This framework encompasses the key urban systems and domains that are shaped and influenced by the design principles and strategies of compact cities and eco-cities as the most prevalent models of sustainable cities. The data flow from these systems and domains as a result of the digital instrumentation enabled by the IoT in terms of the networked sensor devices that are embedded and deployed across urban environments. The IoT-sensor network is in turn connected with cloud–computing infrastructure. Therefore, the data flows are to be stored, managed, processed, and analyzed based on cloud computing solutions. The analytical outcome resulting from these computational processes targets optimization and intelligent decision support pertaining to operations, functions, services, strategies, and policies in relevance to sustainability. One of the essential strands of this framework is the use of the IoT and big data technologies and their novel applications to solve the problems and challenges of environmental sustainability.

Fog computing

Due to the recent advances and cost reduction in sensing technology, sensing is projected to be ubiquitous and thus its capabilities to be integrated into everyday objects around us. Evolving into more sophisticated network of sensors and physical objects spanning nearly all aspects of life, the IoT connects billions of devices and smart things to the Internet. These objects are expected to produce enormous amounts of data and transfer them to the cloud for further processing and analysis, particularly in relation to knowledge discovery, for decision making purposes. However, heavily depending on cloud computing is associated with downsides, notably inefficient computation and communication. Therefore, the fog computing model has been proposed to address the weaknesses inherited by the cloud computing model and to maximize its benefits in regard to managing and manipulating data. More and more industrial IoT platform developers, such as Cisco, IBM, and Microsoft, are moving toward utilizing fog gateway devices to perform edge analytics.

Fog computing (Bonomi et al. 2012) or fog networking (also known as fogging) is a new network architecture that uses edge devices to locally carry out the operations of storage, computation, communication, and networking. Specifically, it is “an architecture that uses one or a collaborative multitude of end-user clients or near-user edge devices to carry out a substantial amount of storage (rather than stored primarily in cloud

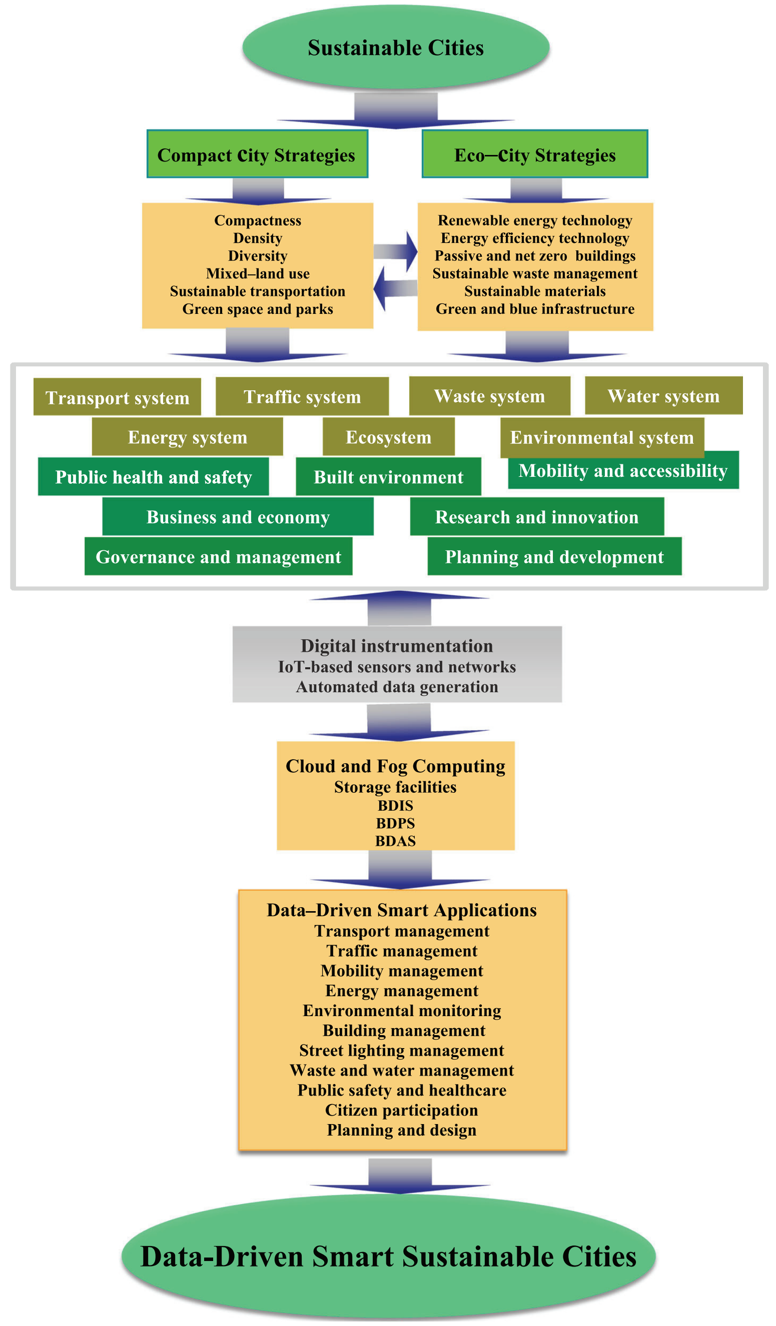

Fig. 4 A framework for data-driven smart sustainable cities
Source: Adapted from Bibri (2020a)

data centers); communication (rather than routed over the internet backbone); and control, configuration, measurement and management (rather than controlled primarily by network gateways …" (Chiang 2015, cited in Perera et al. 2017, p. 3) It facilitates the operations of these services between end devices and cloud computing data centers, and distributes the related resources on or close to the devices in the control of end–users (Zhang 2016; Ostberg et al. 2017), thereby ensuring minimal latency for time-sensitive operations. End devices provide the channel over which the network messages travel. They originate the data that flows through the network. Network switches, routers, and other equipment work in between to enable messages to travel from one end device to the other. These intermediary devices usually direct data over alternate paths in the event of link failures and filter the flow of data to enhance security. However, the fog computing model has been developed due to several reasons, including:

- To respond to the sheer, monumental increase of data bandwidth required by the end devices underpining the IoT.
- The high costs and resource wastage associated with the transfer of all the data captured all the time to the cloud in terms of not only bandwidth, but also storage, latency, network, energy consumption for communication, and so on.
- The constant stream of the data generated has to be validated, processed, and analyzed in real time. Data validation needs to take place closer to the requester. Fog computing can crunch through data at a faster pace or more efficiently compared to cloud computing. It allows disconnected validation of data, a feature which lowers bandwidth costs as it helps reduce the total amount of end to end bandwidth needed.
- The IoT requires processing the generated data much closer to the source in real time to minimize network latency as well as to increase service quality.
- Fog computing handles everything at leaf nodes or at the edges of a network, i.e., edge analytics performed locally.
- With ubiquitous sensing, certain types of data raise security issues in cloud computing as they are sensitive and risky and may be subject to malicious attacks. This poses serious concerns and may trigger cascading effects in database systems.

One of the recent studies on fog computing conducted by Qasem et al. (2020) proposes a smart city based on the concept of fog computing with flexible hierarchy, a design which is intended to overcome the limitations of previous approaches, notably cloud computing, autonomic network architecture, and ubiquitous network architecture. According to the authors, the proposed approach achieves a reduction of the latency of data processing and transmission with enabled real-time applications, allows collaborative data exchange among smart city applications, and distributes the processing tasks over edge devices in order to reduce the cost of data processing. However, while fog computing model has emerged to overcome the shortcomings associated with cloud computing model by pushing data processing and analysis to the edges of a network, both models need to be used when developing the IoT infrastructure for smart sustainable cities (Bibri 2018b) due to their strengths and weaknesses. Perera et al. (2017) provide a comprehensive review of the existing approaches proposed to tackle the challenges of fog computing. Based on this review, the authors identify several major functionalities that should be supported by an ideal fog computing platform, as well as a number of open challenges toward implementing it. They also shed light on future research directions with respect to realizing fog computing for building smart sustainable cities on top of the IoT infrastructure. In relevance to this paper, the authors present an example of future smart power grid (Fig. 5), where fog/cloud computing can play a significant role.

The IoT infrastructure

The ever–increasing big data deluge and the advancement of the IoT have played an important role in the development of smart cities and sustainable cities. This advanced technology is seen as the backbone for building smart sustainable cities of the future. The IoT infrastructure is indispensable to implement data-driven solutions within smart cities and sustainable cities so that they can advance their contribution to the goals of sustainability. An IoT–based infrastructure is necessary to fulfill the needs and visions of smart cities (e.g., Ahmed et al. 2017; Bibri 2018a, 2020a; Hashem et al. 2016; Rathore et al. 2016) and to respond to the goals of sustainable cities (Bibri 2020a; Bibri and Krogstie 2017b, 2020a). Research views the IoT as key to enabling the smart city infrastructure (e.g., Jin et al. 2014) and the sustainable city infrastructure (e.g., Bibri 2018b, 2019b). According to Sicari et al. (2015), the IoT provides a flexible infrastructure within smart cities, which is necessary due to the large number of interconnected devices. Especially, in reference to smart cities of the future, a variety of scanning technologies that range from the region to the individual citizen and to very fine scale

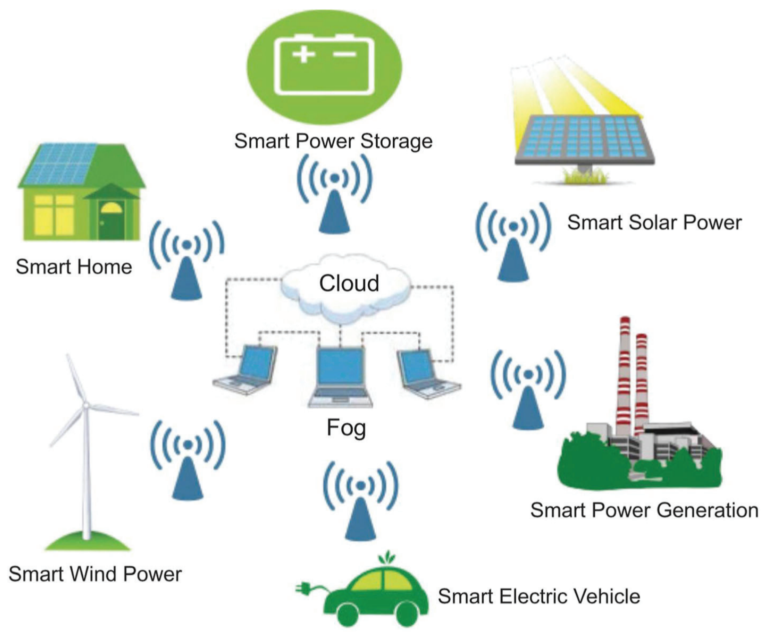

Fig. 5 Smart power grid control Source: Perera et al. (2017)

tagging associated with the IoT are becoming significant. Furthermore, it is important for smart cities and sustainable cities to have an IoT infrastructure where end device connectivity is monitored and communication reliability is assured (Corici et al. 2016; Bibri 2018b) while ensuring that the city sub–systems are intelligent enough to communicate and work in interconnection with each other (Joseph et al. 2017). Also forming a large–scale IoT system with widely deployed devices is key to enabling the IoT services (Cheng et al. 2018) and applications (Bibri 2018b).

For a successful implementation of the IoT in both smart cities and sustainable cities, it is required to have a specific IoT infrastructure in place (Hernández-Muñoz et al. 2011; Bibri 2018b), supporting the complexity of different sensors and their networks set up in urban environments as well as simplifying the composition of interoperable services and applications. Sensor–enabled smart objects are regarded as the essential feature of the interconnected infrastructures of the future.

Several scholars are developing a smart city or sustainable city infrastructure in layers that start with data generation (e.g., Anthopoulos and Fitsilis 2010; Bibri 2018b, 2019a; Jalali et al. 2015; Jin et al. 2014; Khan et al. 2015; Rong et al. 2014). Sensors and devices collecting data and using a dispersed network for transmission is another key part of the IoT infrastructure (e.g., Filipponi et al. 2010; Jin et al. 2014; Jalali et al. 2015; Rong et al. 2014). For example, within the framework of the development of the city Wi-Fi in Barcelona, 590 spots among them 220 in parks had been installed only until 2016, and the number is planned to increase to 1520 new spots in order to extend the Wi-Fi network to cover all buses and underground (Nikitin et al. 2016). A city Wi-Fi can have a significant impact on the communication capabilities of the sensor infrastructure and the data transfer system. However, data flows allow the formation of a layered and generic IoT infrastructure for smart cities and sustainable cities. According to Berkel et al. (2018), the baseline IoT infrastructure for smart cities consists of four layers, namely:

1. Physical layer (sensors)
2. Technology layer (data and application hosting)
3. Application layer (data processing, analysis, and interpretation)
4. Domain layer (smart service delivered after processes)

ICT architecture layers: horizontal Information systems and operations centers

Smart sustainable cities are depicted as constellations of instruments across many scales that are connected through multiple networks characterized by high penetration and speed, which provide and coordinate continuous data regarding the different aspects of urbanity in terms of the flow of decisions about the physical, spatial, environmental, economic, and social forms of the city. This digital instrumentation involves the infrastructure and devices that produce urban big data using the collective tools, processes. methods, techniques, and technologies that also transform the city into a data-driven enterprise (datafication). The generated data in turn enable real-time analysis of city life (computation), as well as provides the raw material for envisioning and enacting more sustainable, efficient, resilient, equitable, and livable cities. As such, it opens up dramatically different forms of urban management. Its essence revolves around the need to coordinate and integrate technologies that have clear synergies in their operation and need to be coupled so that many new opportunities can be realized. The digital instrumentation of the city is the domain of both small and large ICT companies that are providing the detailed hardware and software for what is called the operating system for the smart sustainable city. Examples of urban operating systems include: Cisco CityOS, Microsoft's CityNext, Urbiotica's City Operating System, IBM's Smarter City, and PlanIT's Urban Operating System.

The operating system is a key component of the ICT architecture of the smart sustainable city. In this context, both the data infrastructure and the operating system constitute what is called the horizontal information system for the city, which is a key component for performing the main functions of big data analytics. Functionally compatible horizontal information systems allow the creation of a united ecosystem for the smart sustainable city. They serve to link together diverse smart technologies and solutions to coordinate the city systems by performing the following functions (Bibri 2020a):

– Providing open platforms connecting all the sensors installed in the city and the data obtained from them
– Aggregating and standardizing the flows of functional and territorial data from municipal sources, systems of state control (mobility, energy, noise level, pollution level, etc.), business environment, and other state agencies (hospitals, cultural institutions, universities, etc.), as well as from various detectors and cameras for their subsequent integrated analysis and visualization in 3D format
– Solving the problems of data disconnection in the city through the open operating system integrating and processing the information generated by the city
– Reworking and repackaging the collected data for daily consumption by different stakeholders
– Allowing the city authorities and third party users to gain access to the received data in a more structured and convenient manner for software development
– Enabling comprehensive solutions to complex urban problems by integrating the self-contained and unconnected technological solutions and information systems used in different city functional departments
– Improving the efficiency and performance of implemented applied technological solutions
– Allowing the city authorities and other users to take decisions on the optimization of the city activities in the long and short-term.

There is a range of the ICT architectures that essentially aim to provide the appropriate infrastructure for the functioning of the loT and big data ecosystem in relation to large–scale solutions. These architectures tend to follow similar patterns in terms of their layers. According to Bibri (2020a), the design of the ICT architecture of the smart sustainable city can be based on three main layers, namely information layer, middleware layer, and application layer:

1. The information layer is based on the whole complex of data sources, data routinely generated about the city and its citizens by a range of public and private organizations. This layer collects raw data from different sources within the framework of the smart sustainable city. These sources include sensors, cameras,

transponders, meters, actuators, GPS, and transduction loops monitoring various phenomena, as well as a multitude of smartphone apps and sharing economy platforms generating a range of real-time location, movement and activity data. This layer also includes technologies and solutions allowing the transfer of the collected data for their further processing and analysis. The sensor platform of this layer isolates the applications that are to be developed to exploit the information generated by the smart sustainable city. It also provides openness and interoperability. The data infrastructure standardization and data integration in a unified system significantly simplify the further usage of data.

2. The middleware layer collects raw data from the information layer and standardizes them for further processing and analysis. It provides tools for the storage, processing, and analysis of the collected data, which allow interpreting data, making forecasts on their basis, and identifying interconnection between different data ranges. This set of data analytics techniques enables to obtain the meaningful information from the resulting vast troves of real-time, fine-grained, contextual, and actionable data for numerous applications. It represents the operation system for the city, a platform that offers a comprehensive and transversal connectivity to serve citizens and other stakeholders. It is an open-code IoT platform that is accessible and open for use by third parties: to download, develop, and/or modify.
3. The application layer is the set of applications that use the meaningful information made available from the lower layers, and provides services for the smart sustainable city. It serves for the exchange of data among all the interested parties and the adoption of solutions based on the obtained data. It is based on the idea of using data to predict situations in order to make better decisions and reactions. This layer includes platforms with open data and tools of data visualization (e.g., dashboards and smart board) applied by the city administration for control over the city management system, automated systems of response to city-wide events (e.g., situation centers and control rooms), as well as a plethora of applications developed by city governments, state agencies, and other external developers.

In relation to the IoT component of the ICT infrastructure, the networked sensing devices provide abundant, systematic, dynamic, varied, resolute, relatively cheap data about the city operating and organizing processes, allowing for real–time analysis and adaptive forms of urban management. They are able to continually send information to the management systems in the city that can respond in real time to data flows and adopt solutions. This is associated with what is called urban operations centers and urban dashboards (see the Application layer). These are intended to draw together and interlink urban big data to provide an integrated view and synoptic intelligence of the city. (e..g., Bibri 2019b, 2020a; Bibri and Krogstie 2020b; Kitchin 2014, 2015; Kitchin et al. 2015; Nikitin et al. 2016). Urban operations centers are typically created to monitor the city as a whole; draws together real–time data streams from many different city agencies and departments into a single data analytical center; and then visualize and monitor the vast troves of live service data for real-time decision-making and problem solving. According to Bibri and Krogstie (2020b), the key functions of the analytical center include:

– Using visualization sites to help both expert and no-expert users interpret and analyze information, and to allow citizens to monitor the city for themselves and for their own ends
– Employing integrated, real-time data to track the performance of the city and to communicate the live feeds of real-time information to citizens with respect to a number of areas
– Enabling automated systems to respond to citywide events by making immediate decisions pertaining to various urban areas
– Overcoming urban challenges, keeping citizens up-to-date, and developing applications based on the standardized and published open data
– Creating innovative platforms, promoting big data use and application, introducing data-driven technologies, and providing expert assistance

Results

Stockholm and Barcelona: differences and commonalities

The City Stockholm has a long history of environmental work and was the first city to be granted the European Union's Green Capital award by the European Commission in 2010 due to its high environmental standards and ambitious goals for further environmental improvement (European Green Capital 2009). This includes climate change, air quality, green energy, waste and water management, wastewater treatment, sustainable land use, environmental management, and sustainable transport. The city has a long-term commitment to sustainable development and the environment. Stockholm and SRS received an award for best sustainable urban development project in the category Sustainable Communities, which was presented at the UN Climate Change Conference in Paris 2015 by the C40 Cities Climate Leadership Group, a network connecting more than 80 of the world's megacities (Stockholm City 2020). The award is proof that Stockholm is an international leader in sustainable urban development.

According to several rankings, Sweden is one of the leading countries that have the highest level of sustainable development practices (Dryzek 2005). Another recent ranking has been reported based on 2018 Environment Performance Index (EPI) data: Sweden is one of the world's leading countries in sustainability and has an overall score of 80.51 in terms of environmental friendliness (Buder 2019). Sweden and the rest of the Nordic countries have a comparatively low impact in terms of CO2 emissions (Norden 2008). In fact, several empirical studies identify from the mid–1980s onward an increasing ecological disruption in most of the ecologically advanced nations, such as Sweden, Denmark, Germany, and the Netherlands (Mol 2000).

Stockholm is at the forefront of ecological/environmental thinking. It has very strong environmental policies and is focused on improving the quality of life of its citizens (Lindström and Eriksson 1993; Stockholm City 2018) with support of advanced technologies (Bibri 2020a; Evertzen et al. 2018). According to the City of Stockholm, an IoT–based infrastructure is highly important for, and the backbone for building, smart sustainable cities nowadays (Bibri and Krogstie 2020a). As stated by Johansson (2018), a project leader, "the reason we are establishing this is because we have a lot of challenges. We know that using the smart technologies can help us to be a better city, for the people that live there, work there and even the people that are visiting us." He also stated that the environmental department in the city is active with smart technologies. During the period 2015–2016, an ICT network was established in the City of Stockholm to find a more comprehensive way of using ICT, and the digital development department of the city was established with a much broader take on ICT (Kramers et al. 2016). The city has recently taken concrete actions for using data-driven technologies to reach its environmental targets by 2040, in particular in relation to the initiatives of its sustainable urban districts (Bibri and Krogstie 2020a).

In recent years, much of the environmental work within Stockholm has focused on developing new sustainable urban districts. One recent initiative is the Stockholm Royal Seaport (SRS) district, whose vision is to become a *"*world class environmental city district*"* (Stockholm City 2010). SRS is designated as an environmental profile area with the mandate to become a model of sustainable urban development (Stockholm City 2020). The vision of SRS relates to the overall goal established by the City of Stockholm to be fossil fuel–free by 2050 (Stockholm City 2009, 2018). In this respect, SRS environmental profile should consolidate Stockholm's position as a leading capital in climate work and contribute to the development of new technologies (Bibri 2020a, b). The smart eco–city district of SRS starts with a common vision in smart planning on the basis of the IoT technology (The Nordics 2017).

The City of Barcelona started to develop its smart city scenario during the period 2007–2012, leveraging its telecommunications network. In 2011, it became one of the first European cities to implement data-driven smart technologies to improve its services. It invested heavily in its ICT infrastructure, including an extensive IoT sensor network collecting data on many urban systems and domains. It has brought the IoT to life (Adler 2018). Confidence in advanced ICT as a tool for supporting urban development was extremely widespread within the Municipality of Barcelona before 2011. Implemented in Barcelona is a broad range of applied technological solutions based on the analysis of the data generated by a variety of sources, with the aim to improve the quality of life of citizens. Barcelona created a new model for the management of services, relationships, and interactions with citizens based on e-government and developed different pilot projects by both the private municipal company 22@ Barcelona and the Municipal Institute of Information Technology (Mora and Bolici 2016; Noori et al. 2020). In addition, the Barcelona City Council and Municipal Institute of Informatics jointly cooperated in 2012 to set the basics of an architecture defining the strategies and policies allowing Barcelona to become a Smart City. According to Sinaeepourfard et al. (2016), the Barcelona Smart City ICT architecture has been designed with three main layers, namely the Information Sources layer, the Middleware layer, and the Smart City Applications layer (see Fig. 6).

- The Information Sources (IS) layer aims to collect raw data from the Smart City's different sources.
- The Middleware layer collects raw data from the IS layer, and provides some processing and analysis procedures to obtain the meaningful information as feeds for abundant applications.
- The Smart City Application layer is the set of applications that use the required meaningful information from low level layers and provides services in connection with the city management.

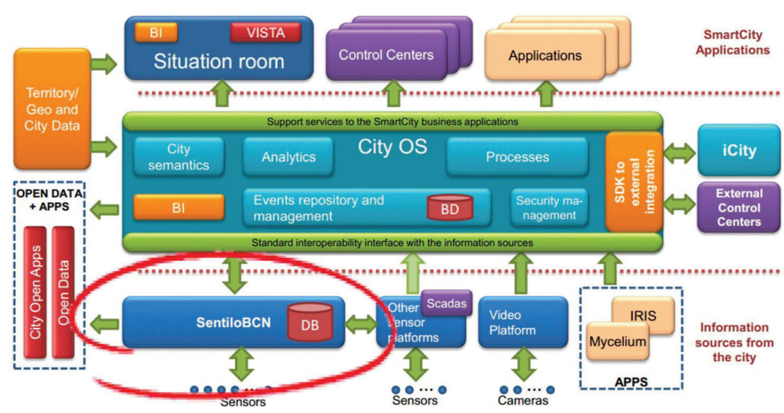

Fig. 6 Barcelona Smart City ICT architecture. Source: Sinaeepourfard et al. (2016)

In 2015, Barcelona took the initiative of the smart city in a new direction by setting the goal of democratizing its ICT infrastructure, with a vision of developing it by and for the people (Bibri 2020a). The aim of the city is to exploit digitization and achieve a city that is more open, fair, circular and democratic by putting technology at the service of people.

Moreover, the City of Barcelona is mostly reputed for using data-driven technological solutions in urban operational functioning and management, and what this entails in terms of competences, infrastructure, and data sources (e.g., Bibri 2020a; Nikitin et al. 2016; Sinaeepourfard et al. 2016). The smart city strategy has been properly included in the strategic framework of the City of Barcelona in line with the objectives, priorities, and directives that characterize it (Mora and Bolici 2016). The attempt to transform the city into a smart city has been translated into a series of endeavors and initiatives managed by various executive units of the city administration. This has been supported by establishing a number of projects, constructing the public Wi-Fi network, and implementing several planning measures to modernize the city's ICT infrastructure and to strengthen its readiness to apply data-driven smart solutions for supporting sustainable development and the environment (Bibri and Krogstie 2020b). Barcelona is building one operating system that would run the entire city on a single interface, and aims, in pursuing such technology-driven upgrades, to serve as a model for other cities in technology-led urban transformation and management (Eden Strategy Institute 2018). According to Cisco's estimates, Barcelona's current smart city investments should return a cumulative economic benefits of USD 970 million by 2026 (Bibri 2020a). In addition, the city has a strong commitment to becoming a show-case for the rest of the world in sustainable urban development (Mora and Bolici 2016). One of the strategies of the Municipal Action Program is called *"urban renewal"* and is associated with a precise strategic commitment to transform *"Barcelona into a sustainable, smart urban model at the service of its residents"* (Mora and Bolici 2016, p. 3).

Data-driven solutions for energy efficiency and pollution reduction

Both smart cities and sustainable cities (notably eco-cities) are increasingly embracing data-driven technologies and their novel applications in the area of energy and environment. This is due to the high potential opportunities being offered by the IoT and big data analytics for advancing environmental sustainability. There is a huge range of the IoT-enabled data-driven applications that are compatible with the goals of environmental sustainability in the context of smart sustainable cities, spanning diverse urban systems and domains.

Smart grids and smart meters

Both smart cities and sustainable cities are increasingly investing in and implementing smart meters, sensor networks, automated control systems, and cyber-physical systems in the area of smart energy within the framework of the IoT. The main players in this area are smart power grid and advanced metering infrastructure (AMI), Smart power grid denotes a set of software, hardware, and network tools that enable generators to route power more efficiently to consumers, reducing the need for excess capacity and allowing two–way, real-time information exchange with users and consumers for real-time demand side management. It integrates and coordinates renewable energy production and consumption and power facilities through enabling technologies, energy services, and active users. AMI is a composite technology which consists of solid-state meters capable of remotely providing electricity use detail to utility companies, a two-way communication channel, and a meter data repository and management.

Stockholm Stockholm argues that climate–adapted solutions will minimize energy use (Stockholm City 2009). In this respect, the city aims to use digitalization and new technologies to make it easier for residents and businesses to reduce energy consumption and carbon footprint and thus become environmentally friendly (Stockholm City 2017). As stated in the Master Plan for Stockholm, Stockholm's eco-development SRS is currently trialling smart electricity grids (and integration of district heating with low-energy housing) (Stockholm City 2018). The Smart Eco-city District of SRS has implemented a large–scale smart grid system, which comprises the following 7 components (Bibri 2020a, b):

1. Smart homes/buildings and demand response
2. Distributed energy systems
3. Integration and use of electric vehicles
4. Energy storage for customers and the grid
5. Smart electrified harbor
6. Smart primary substations
7. Smart grid lab (part of an innovation center)

Brandt and Nordström (2011) identify how 150 indicators spanning electricity, district heating, transportation, water, waste, and a number of other environmental and social factors, can be integrated with the SRS-M Information Management System (SRS-M IMS). Based on a functional gap analysis, the authors demonstrate that the

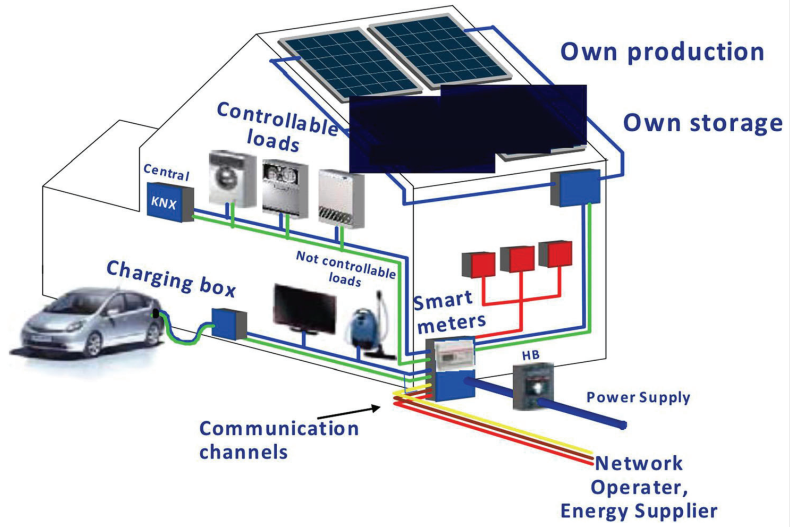

Fig. 7 Local production of electricity. Source: Bibri and Krogstie (2020a)

smart grid as the anchor of smart cities partially enables less than 15% of the 150 indicators initially proposed in the SRS-M.

SRS aims to take the lead in realizing the latest innovations within smart and green technologies. In particular, it affords great opportunities for climate–adapted and future–oriented development, from pioneering energy–efficient technical solutions in building and infrastructure to the development of smart electricity networks that enable local production and distribution of electricity (Stockholm City 2009). As to the local production, the municipality set these energy requirements on urban developers: 55 kWh per m2 x year and 30% locally produced electricity by renewables (see Fig. 7). Both requirements are associated with the energy goals set by SRS (Stockholm City 2009, 2010), most of which are relevant to this study as presented in Table 2. Opportunities for the local energy production should be promoted in urban development, and for maintenance reasons, passive solutions should be given priority over more technology-heavy alternatives (Stockholm City 2018).

The IoT allows for observing energy consumption and monitoring GHG emissions in real-time across several spatial and temporal scales so to curb energy usage and reduce

Table 2 Relevant energy goals of SRS

• Fossil fuel free by 2030
• Locally produced solar energy—electricity by renewables.
• Smart grids for electricity (and heat).
• Energy quality hierarchy (using high energy quality only when needed).
• Low level of energy use concerning products and systems.
• Low level of energy use concerning systems
• Measuring energy usage in all households/buildings

Source: Adapted from Bibri and Krogstie (2020a)

GHG emissions. This entails that the smart grid system collects the data from diverse power sources and then process and analyze them in real-time for decision-making by transmitting relevant information for process control to improve the performance of the power grid. This involves using AMI, which includes sensors placed on consumers access points and on production, transmission, and distribution systems, as well as remote controls and communication technologies within electricity networks (Fig. 8). In other words, the operation of the smart grid system involves ICT system integration, data, and back office, which allow the integration of front-end engineering, middleware, and computing systems, as well as data collection and decision analytics.

Number 1 in Fig. 8 represents the customer application support in terms of in-home display with real-time usage and pricing statistics, usage aware appliances, and home automation. These pertain to the data-driven smart applications associated with demand side management, which allow:

- Users to manage their usage based on what they actually need and afford by having access to live energy prices and adjusting their usage accordingly;
- Self–optimizing and –controlling energy consumption through integrating sensing and actuation systems in different kinds of appliances and devices for balancing power generation and usage;
- Users to remotely control their home appliances and devices based on the IoT by means of such advanced functions as scheduling, programming, and adapting to different contextual situations; and
- Providing insights into how the energy flows can be influenced by the user behavior thanks to the in-house sensors that can provide data on energy-using appliances.

At the technical level, as illustrated in Fig. 8 under number 2, the smart meters record information on the consumption of electric energy, electric current, voltage levels, and power factor in near real-time. And they communicate this information to the consumer for the greater clarity of the consumption behavior, as well as to the energy supplier for system monitoring and customer billing. AMI enables a two-way digital communication between the meter and the central system supported by computer processing technologies, has the ability to report usages by time and outages in real-time, reduce load, disconnect-reconnect remotely, interface to water meters, and improve operation for distribution companies. In relation to the first bullet point stated above, for example, utilities have the ability to collect a significant amount of "siloes" data as part

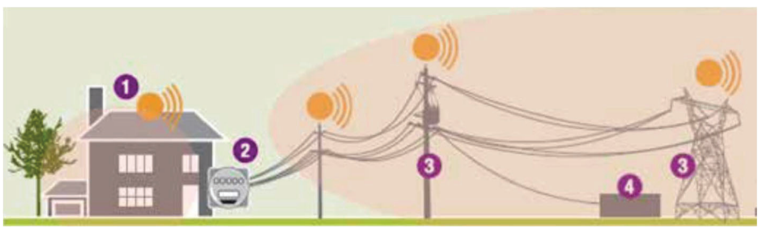

Fig. 8 Data-driven smart energy solutions in SRS. Source: Bibri (2020b)

of their activities through the implementation of AMI technologies. These can provide instantaneous individual and aggregated information on energy flows for households, and be used to impose caps on consumption and also enact various revenue models at the request of the consumer to control costs. This involves the use of pricing plans in accordance with energy demand and supply models. Smart metering is also key to avoiding the expensive and carbon-intensive peaks in power grid, using new ways of coordination as to the overall ensemble of consumers; it provide new means for aggregating real-time data on energy consumption and defining dynamic prices schemes (Bibri 2020b).

In addition, number 3 in Fig. 8 is associated with the grid applications drive: automation of the grid, reduction in losses, remote monitoring, and more accurate balancing. These pertain to the data-driven smart applications concerned with power supply management handled by the smart grid system, which include:

- Optimizing power distributed networks associated with energy demand/supply
- Monitoring and analyzing energy consumption and GHG emissions levels in real time across several spatial scales and over different temporal scales
- Enhancing the performance of the central power system
- Managing distribution automation devices to improve the reliability, stability, and resilience of power production and distribution
- Enabling energy systems to gather and act on (near) real–time data on power consumption, generation, and inefficiency from end–user connections (information about producers and consumers' behavior)
- Avoiding potential power outages resulting from high demand on energy using dynamic pricing models for power usage by increasing charges during peak times to smooth out peaks and applying lower charges during normal times.
- Avoiding the expensive and carbon–intensive peaks in the power grid using new ways of coordination with regard to the overall ensemble of users and consumers
- Supporting decision–making pertaining to the generation and supply of power in line with the actual demand of citizens and other consumers to optimize energy efficiency and thus achieve energy savings.

As illustrated in Fig. 8, the communication from the meter to the network operator is wireless. Wireless communication options are in fact of common use in this regard, and include, but are not limited to:

- Wi-Fi (readily available)
- Wireless ad hoc networks over Wi-Fi
- Wi-SUN (Smart Utility Networks)
- Wireless mesh networks

Worth noting is that wireless communication is of paramount to the functioning of the IoT and the spread of its data-driven applications across the city, beyond the domain of energy. A most popular form of government-sponsored Internet access is seen in the form of public Wi-Fi spanning different city districts in Stockholm as well as Barcelona.

Number 4 in Fig. 8 is associated with integrated renewables and distributed energy. This facilitates the integration of back-up generators, storage, and distributed solar, as well as disconnection in case of network overload (Bibri 2020b). In terms of the distributed solar and wind stations, the use of these applications are intended to improve coordination and planning around power generation from renewable plants depending on the wind or sun. Quire good estimations of power generation from wind, solar panels, and photovoltaic plants can be made a few days in advance thanks to the weather forecast. It is well conceivable, for instance, to offer a better price for electricity on a windy or sunny day and thus create an incentive to use this carbon neutral energy at a certain time.

Stockholm strongly advocates renewable energy generation in order for SRS to become fossil fuel–free by 2030. The future energy system in SRS is intended to be based on renewable sources. This is very crucial for the district to fulfil the ambition of becoming environmentally sustainable (City of Stockholm 2010). Every part of the district that is affected by the energy system, e.g., buildings, infrastructures, and systems, must be highly effective and efficient in order for the district to become climate-positive district, especially SRS is part of the Clinton Climate Initiate (City of Stockholm 2010).

Smart buildings

The building management system (BMS) is an overarching computer-based control system (an intelligent distributed network of electronic devices and systems) that is responsible for the automatic regulation, control, and monitoring of the building or facility's mechanical and electrical subsystems, such as heating, ventilation, air conditioning (HVAC), lighting, power systems, and security systems. These technical processes are primarily intended to maintain predefined parameters (or set points) and the control of their functionality. The BMS uses smart metering and advanced visualization tools to provide real-time monitoring and continuously gather the data on what is taking place in a building and how its equipment is operating and feeding these data into a control system to improve energy efficiency. So, the collected data can be used to identify additional opportunities for improvements.

Smart eco-cities are making substantial efforts towards meeting their climate change commitments and thus achieving their environmental targets—with support of data-driven smart technologies and solutions—in response to their national and local policies. Applied in Stockholm, in addition to existing and newly constructed smart buildings, is a novel data-driven smart approach to strategic planning of building energy retrofitting, which is based on the urban building energy model (UBEM), using data about actual building heat energy consumption, energy performance certificates, and reference databases (Pasichnyi et al. 2019). This approach allows a holistic city-level analysis of retrofitting strategies thanks to the aggregated projections of the energy performance of each building, such as energy saving, emissions reduction, and required social investment. Three retrofitting packages: (1) heat recovery ventilation, (2) energy-efficient windows, and (3) a combination of these, are considered for the multi-family residential buildings constructed between 1946 and 1975. The identified potential lies in decreasing heat demand by 334 GWh (18%) and consequent emissions reduction by 19.6 kt-CO2 per year in the City of Stockholm, which demonstrates the potential of rich urban energy datasets and data science techniques for better decision making and strategic planning. The proposed approach allows the change in total energy demand from large-scale retrofitting to be assessed, and explores its impact on the supply side, thereby enabling more precisely targeted and better coordinated energy efficiency programs. Prior to this study, Shahrokni et al. (2014b) evaluate the energy efficiency potential of different building vintages in the City of Stockholm in collaboration with the district heating and electricity utility Fortum. The authors found that the retrofitting potential of the building stock to current building codes can reduce heating energy use by 1/3. In terms of market segmentation, the greatest reduction potential in total energy was found to be for the buildings constructed between 1946 and 1975 due to their poor energy performance.

Limiting or alleviating pollution levels requires a substantial decrease in the average carbon intensity of buildings. This in turn requires using decision-support systems that enable largescale energy efficiency improvements in the existing building stock. Among the common hurdles preventing the widespread adoption of energy efficiency measures in buildings are: poor design of buildings, which makes it difficult to implement BMS and to apply common standards for efficiency and operation; lack of incentives or funding schemes for architects, builders, and developers to invest in smart building technology; and reluctance of building owners to accept too much built-in automation. The most effective approach to overcome these hurdles and thus realize the full potential of advanced ICT is to design innovative policies, including developing strong frameworks to encourage consumers to adopt these technologies, providing incentives for consumers or other types of intervention, and raising awareness of the benefits of ICT-based climate solutions.

Barcelona As part of the new study: Smart Cities: Strategies and Forecasts in Energy, Transport and Lighting 2017–2022, Juniper (2020) analyzed five global cities to assess their performance and approach towards energy consumption and delivery, and one of their conclusion is that smart meter roll-outs, as well as several smart grid, such as the GrowSmarter initiative, are being deployed to deliver low-to zero-emissions zones in Barcelona. With the roll-out of smart metering devices and novel software applications, the IoT has made it possible to reorganize and coordinate demand and supply, using new pricing and billing mechanisms, based on the energy market and production (Bibri 2018b). Additionally, however, the MONICA project develops a system capable of precisely establishing the status of the distribution grid in real time and at any given moment (Status Estimator), which provides real and immediate information about the impact on the quality and safety of the supply (Nikitin et al. 2016). This project deploys an entire network of medium and low voltage sensors that record measurements for all the electrical variables needed to be entered in the grid's new Status Estimator. This receives the collected data in real time via the deployed sensors and the existing smart meters diagnosing the different problems on the grid in order to prevent or improve them, as applicable. As regards BMS, one of the main categories of energy monitoring management system in Barcelona is installed in municipal buildings, where sensors obtain information about energy consumption, such as electricity meter, electricity ambient conditions, internal ambient conditions, and temperature (Sinaeepourfard et al. 2016).

Worth pointing out is that the smart meter roll-outs and several smart grid projects were developed in Barcelona and Stockholm during approximately the same period of time. Moreover, most of the data-driven smart energy solutions associated with SRS, as explained and elaborated on earlier, apply to Barcelona from a technical and operational perspective, with some key differences in the degree of the development of data-driven technologies and competencies. In particular, the sensor infrastructure is largely developed proportionally in the two cities. Barcelona has a denser network of sensors which compile data from a wide variety of sources. Also, the city must have significantly improved its public Wi-Fi network whose construction was, according to many studies (e.g., Bibri and Krogstie 2020b; Mora and Bolici 2016; Nikitin et al. 2016; Noori et al. 2020; Sinaeepourfard et al. 2016) launched during the early 2010s. A city Wi-Fi can have a significant impact on the communication capabilities of the sensor infrastructure and the data transfer system, which is of utmost importance to the operation and functioning of smart grids and AMIs, as illustrated in Fig. 8. Barcelona has declared its intentions to become the most connected city in the world and is following through on its promise by investing considerably in the IoT infrastructure and thus sensor network for the city (Eden Strategy Institute 2018). It has recently become an interesting location for Cisco to open a global innovation center for the IoE paradigm and architecture. In addition, the two cities slightly differ in the degree of their readiness as to the availability and development level of the ICT infrastructure and competencies needed to generate, transmit, process, and analyze data to extract useful knowledge for enhanced decision making and deep insights pertaining to environmental sustainability uses and applications. Barcelona has the best practices in the ICT infrastructure, especially horizontal information platforms, and in the operations centers as a data-oriented competence. It was only recently when the City of Stockholm has established a platform for data collection after realizing the importance of coordinating and orchestrating the plethora of the different systems that constitute the ICT infrastructure (Bibri 2020a). In relation to the SRS project, the City of Stockholm was still in the mid 2010s "working on securing structures and databases for collection of data that can be used to give feedback and inform inhabitants and also sort out a viable business model for the data collection unit" (Kramers et al. 2016, p. 104). Further, Barcelona and Stockholm both have these data-oriented institutional competences: educational centers and training programs, innovation and research centers, and strategic planning and policy offices (e.g., Bibri 2020a; Bibri and Krogstie 2020a, b; Mora and Bolici 2016; Nikitin et al. 2016; Noori et al. 2020; Kramers et al. 2016). Nevertheless, Stockholm has higher degree of the implementation of applied technology solutions in data-driven city management in relation to environmental sustainability compared to Barcelona:

- The development of applied data-driven solutions for city operational functioning and city development planning in the area of energy and the environment.
- The establishment of city competences with respect to environmental education, research, innovation, and strategic planning and policy.

In relation to number 4 in Fig. 8, Barcelona has invested in smart energy in terms of photovoltaic panels, thermal solar panels, and energy modernization. According to Noori et al. (2020), Barcelona Energia's energy transition model has the mission of producing a 100% certified renewable energy supply plan through smart energy (Barcelona Self-sufficient Energy Plan 2014–2024). According to de Barcelona (2018), 73 projects for installing solar energy panels in the different parts of the buildings have been established as part of the Program for Promoting Solar-Energy Generation, in addition to the 87 solar energy installations already distributed around the city, as reported by Barcelona Energia. According to Sinaeepourfard et al. (2016), energy monitoring management includes two main categories installed in municipal buildings and solar thermal installations. The data on energy consumption are obtained from the sensors installed in the municipal buildings, and the solar thermal installation aids the city in understanding the solar thermal energy produced and consumed. The number of components, frequency of measure, frequency of sending and updating information, and some other information details are presented in Table 3.

Concerning the local production of electricity by renewables, considered to be the first regulations of their kind to be enacted in Europe, Barcelona has required the use of solar water heaters by households since 2006, as well as new large buildings to produce their own domestic hot water since 2000 (Bibri and Krogstie 2020b). For a recent and detailed study on the renewables in Barcelona, the interested reader can be directed to Juniper (2020). On the whole, renewable energy systems are among the key data-driven smart solutions adopted by the City of Barcelona as to supporting its smart grid system.

In addition, Barcelona is home to one of the larger electric vehicles (EV) charging networks among the five cities analyzed by Juniper (2020). Like Stockholm, EVs are rapidly gaining mindshare among consumers in Barcelona. However, smart grid technologies that go hand-in-hand with renewables, such as solar, wind, wave, hydro and geothermal power, are required due to the energy demands of the massive adoption of EVs. This raises the question of how renewable energy should be integrated with the existing grid at scale, and therefore, storage solutions are required, so are mechanisms for decentralized energy generation, sharing, and sale. The IoT can enable new mechanisms for trade on the basis of supply and demand in the energy market.

Table 3 Energy monitoring management

Type	Number of devices	Frequency of sending and updating information
Electricity meter	28	Every 1 min (instantaneous data) and every 15 min (average data)
External ambient conditions	7	Every 1 min (instantaneous data) and every 15 min (average data)
Gas meter	1	Every 1 min (instantaneous data) and every 15 min (average data)
Internal ambient conditions	41	Every 1 min (instantaneous data) and every 15 min (average data)
Network analyzer	421	Every 1 min (instantaneous data) and every 15 min (average data)
Solar thermal installation	36	Every 15 min
Temperature	7	Every 15 min

Source: Sinaeepourfard et al. (2016)

The role of policy in smart sustainable grids and buildings The vision of smart grids proposed by the two cities has triggered a broad range of research, development, and demonstration projects that aim to facilitate the development and modernization of their power grid on the basis of modern technologies. This is justified by the benefits of smart grids, which allow for monitoring, analysis, communication, and control within the energy supply chain to help optimize energy efficiency, curb energy usage conserve energy, maximize the transparency and reliability of the energy supply chain, and decrease costs. Concerning the latter, new data from Juniper Research (2020) has found that the development of smart grids will result in citizens saving $14 billion per annum in energy bills by 2022. This is up from the $3.4 billion saving estimated for 2017, resulting from smart meter rollouts, energy-saving policies, and sensing technology to improve grid reliability and efficiency.

Considering the above benefits, the development of smart grids has resulted from the emergence of new policies in Stockholm and Barcelona, which are essentially concerned with supporting projects of smart grid technologies; subsidizing projects that accelerate efficiency technology adoption; allowing decentralization of energy production; encouraging energy production from renewable sources; promoting multiplication of grid distribution networks; and subsidizing renewable energy integration in power distribution network. The successful implementation of these policies has been essential to addressing barriers to the deployment of smart grids and to meet the emerging challenges, such as climate change, energy security, equity concerns, and privacy protection. With respect to the latter, for example, Barcelona has developed three strategic initiatives related to data protection and regulation: “Data Commons Barcelona,” “City Data Analytics Office,” and “Decode” (the EU’s scientific) project (Calzada 2018), Data Commons Barcelona offers an open-source policy toolkit regarding ethical digital standards “for cities to develop digital policies that put citizens at the center and make governments more open, transparent, and collaborative” (Ajuntament de Barcelona 2020). However, there are major barriers to the development of smart grids-- see “Policy Issues in Sustainable Smart Grids” by Brown and Zhou (2013), as well as significant challenges for their implementation (Ahmadiahangar et al. 2020) that need to be addressed. It is crucial to overcome these barriers and challenges in order to develop and deploy ICT–based energy efficiency and climate solutions so as to realize full GHG emissions reductions opportunities. And policy makers need to identify more effective mechanisms to get producers and consumers to use more innovative ICT-based solutions in ways that support reductions in GHG emissions to levels that are economically, environmentally, and socially sustainable. Indeed, advanced ICT cannot act in isolation to mitigate climate change, nor can environmental practices become widespread with free will. Policy is a salient factor for any societal transition or transformation, in particular sustainability. Bibri (2019f) argues that political action is of critical importance to, if not determining in, the emergence, materialization, expansion, functioning, and evolution of data-driven smart sustainable cities as an academic discourse. In fact, this emerging paradigm of urbanism— is not an element closed in the “ivory tower” of the research community, but it is influenced by the macro-political practices in connection with sustainable development. Among the common political mechanisms used in this process, which represent facets of the operations that link this discourse and political action, include:

- Creating regulatory and policy instruments and carrying out legislations.
- Assigning scholarly roles and institutional positions to particular universities and organisations, thereby authorizing them and legitimising their actions in regard to R&D activities, technology and innovation, policy recommendation, vision construction, and so on.
- Government involvement in projects and initiatives through funnelling investments, providing positive incentives, advocating product and service adoption, organizing forums and symposiums, encouraging national and local programs, and devising comprehensive plans.

Policy remains more important than technology to smart sustainable cities. Most of the data-driven smart solutions that are being rolled out are only plasters that fail to address the wider environmental issue of climate change. This implies that policy must be put into place to maximize the benefits of such solutions through more effective measures. Specifically, smart sustainable cities should have a set of specific policies to ensure that progress is made in any area of environmental sustainability where innovative solutions need to be implemented. With reference to SRS, the smart sustainable city "is fundamentally dependent on the initiative by and interest of other actors—that *developers* see it as relevant to install smart metering devices, that *energy companies* see it as relevant to provide information about energy use to their customers, that *inhabitants* see it as relevant to equip their homes with 'smart' appliances—and, moreover, that the initiatives of these actors in some way are coordinated so that they can in fact support each other. Otherwise there is a risk that technology is not implemented all the way" (Kramers et al. 2016, p. 99). Policy has a primary role in aligning and mobilizing different stakeholders in the same direction. As stated by Bibri (2019f), political processes represent the set-up under which dynamic networks of urban actors can interact within diverse urban sectors in the development, diffusion, and utilization of knowledge and technology pertaining to data-driven solutions in the context of smart sustainable urbanism.

Furthermore, to avoid the failure of the enabling potential of the IoT and big data technologies for improving energy efficiency and hence minimizing the impacts of energy consumption on the environment, it is important to strategically analyze and holistically design policies to ensure that the implementation of data-driven smart solutions make a concrete contribution to the environment. The new policies that aim to encourage or require the use of advanced ICT to mitigate climate change should be evaluated carefully in terms of their ability to absolutely reduce GHG emissions, not merely to slow down their rate of increase. Appropriate policy frameworks can provide the incentives needed to act and innovate to curb energy use and alleviate pollution levels. However, policy tools should include both incentives and prohibitions through a mixture of regulation, co–regulation and self–regulation; top–down and bottom–up approaches to policy development and implementation; and governance arrangements that engage all stakeholders in their roles as citizens and consumers.

In connection with the study conducted to evaluate the energy efficiency potential in the City of Stockholm mentioned earlier, Shahrokni et al. (2014b) found that the least energy-efficient buildings in the city are those built between 1926 and 1945 in contradiction to commonly held beliefs, and the large number of buildings constructed between 1946 and 1975 have poor energy performance. Their findings indicate the need for a shift in public policy towards the buildings with highest retrofitting potential. This applies to Barcelona as well. Indeed, to enable the full enabling potential of advanced iCT requires designing and implementing a number of policies. These include rewarding the best–in–class buildings' owners and operators; incentivizing operators to retrofit their buildings, providing funding schemes to owners to invest in BMS, subsidizing design and district development projects supporting energy efficiency technology adoption; developing energy efficiency building assessment tools; regulating the application of automation measures in the construction of buildings, developing strategic alliances between city governments and industries, and so froth.

Environmental monitoring: air and noise pollution

Stockholm According to 2018 Environment Performance Index (EPI), Sweden stood out for high scores in air quality among the world's five most environmentally friendly countries (Buder 2019). And Stockholm leads in Sweden given its progressive environmental performance and strong environmental policy. The City of Stockholm has made substantial efforts towards meeting its climate change commitments, including a GHG emission target of 3 t per capita by 2020 and making SRS a candidate of Clinton Climate Initiative's Climate Positive Program (Shahrokni et al. 2014b). SRS as a world–class environmental city district has set three ambitious environmental goals (Stockholm City 2020):

1. To reduce CO2 emissions from 4.5 t in 2008 to a level below 1.5 t per inhabitant by 2020.
2. To be fossil fuel–free and climate + by 2030.
3. To be adapted to a changed climate, i.e., increasing precipitation.

One of the key strategies of the environmental program for SRS to achieve the aforementioned energy goals is "resource efficiency and climate responsibility" (Stockholm City 2020). The focus of this strategy is to develop SRS as a district that strives for a fossil-fuel-free and low-resource future. Energy flows are designed to minimize environmental and climate impacts. In addition, the local production of electricity through solar panels is required due to the awareness that GHG emissions in Stockholm mostly come from heating (42%) and electricity (20%) (Bibri 2020a). However, there are a number of barriers to adopting data-driven smart solutions and realizing the full opportunity of GHG emissions reductions, especially in relation to buildings.

However, the use of ICT in the SRS project pertains mainly to its role in and potential for reaching the environmental targets set by the SRS district as part of the digital city plan developed for this purpose (Bibri and Krogstie 2020a; Kramers et al. 2016). In short, it is largely associated with environmental planning. The interview showed that the database systems for collecting the environmental data on SRS were secured and used to inform the residents about different aspects of energy and GHG emissions. The strategic implementation of ICT was brought in to SRS by the environmental program for the City of Stockholm, which requires the district to be smart in the area of environmental sustainability (Bibri 2020a, b). Among the smart sustainable solutions implemented by SRS are the establishment of digitalized monitoring and feedback processes (e.g., the IoT and visualization) (The Nordics 2017). With respect to the IoT, one of Stockholm's main domains is air pollution, in addition to smart grids, smart lighting, smart traffic, and environmental policies. The small–scale tests performed within the different areas of the city to see if smart technologies work have been converted into pilot projects within these domain (Johansson 2018). With respect to air pollution, the sensors connected to the city's Wi-Fi network report in real-time the air pollution level concentrated in particular urban environments and provide real-time information about the air quality in the city. The IoT has great potential to improve air quality. This is usually achieved by deploying and setting up stations for environmental monitoring across the city, as well as mounting sensors on bike wheels and cars for measuring the air quality. The collected data can be used to make inferences about the quality of the air. Then the outcome can be transferred to the decision-making unit for implementing pollution preventive measures to remove different types of pollutants detrimental to public health. The air quality monitors are operated by regulatory agencies, citizens, as well as researchers to investigate the air quality and the effects of air pollution. Commonly, the interpretation and analysis of ambient air monitoring data involves a consideration of the spatial and temporal representativeness of the data gathered, and the health effects or risks associated with the exposure to the monitored levels.

Barcelona Air pollutants as atmospheric substances—especially anthropogenic—have negative impacts on the environment, as well as pose a high environmental risk to human health, so too is noise pollution, both direct and indirect. Noise pollution denotes harmful outdoor sound with road traffic being the greatest contributor. The demand for the smart systems that monitor the quality of the environment has increased due to the elevation of pollutants in the atmosphere The escalating urbanization trend leads to the environmental degradation of the air. Nevertheless, new and emerging technologies allow a real-time tracking of the various substances in the air and applying preventive measures in a timely manner. For a city to have the best air quality, it must significantly reduce GHG emissions from its energy and transport sectors, and to become zero-carbon. According to the Municipal Action Program for Barcelona, the city has to achieve a significant objective: the definition of a new development model for a healthy and hyper-connected city with zero emissions *"where the environment, urban planning, and ICT infrastructures are fully integrated"* and characterized by *"productive neighborhoods at a human pace"* (Mora and Bolici 2016, p.4). Many recent studies on Barcelona focus on the impacts of energy consumption on the environment, control over transport flows and their effects on the noise level, and car exhaust gases (Bibri and Krogstie 2020b; Nikitin et al. 2016).

Table 4 Noise monitoring management

Type	Number of devices	Frequency of sending and updating information
Noise	3	Every 15 min
	40	Every 1 min
	10	Every 1 min

Source: Sinaeepourfard et al. (2016)

In Barcelona, the solutions devised for control over air pollution entail the analysis of the data collected from sensors on the level of air pollution in the different districts of the city to alleviate it. And the solutions devised for noise pollution control involve the analysis of the data collected from sensors on the level of noise pollution for planning of work to reduce it. The environment monitoring system is based on the data automatically collected from the sensors installed across the city. It has been implemented in the framework of a pilot project, and allows users to collect data about the noise level, air pollution, temperature, and humidity by special sensors, which are transmitted via Wi-Fi network in real-time mode to social centers (Nikitin et al. 2016). The recorded data is used to analyze the effects of the measures taken or the impact of the solutions adopted to improve the environmental conditions of the city, compile further programs for environment protection, and identify the areas where further actions are to be undertaken (Bibri and Krogstie 2020b).

From a technical perspective, the Sentilo platform, as mentioned earlier, collects the city data provided by the network of sensors for city management. Up till 2016, there were almost 1800 sensors installed as part of the Sentilo platform in Barcelona, monitoring data about different areas, including noise monitoring (Sinaeepourfard et al. 2016). Noise monitoring management detects any kind of noise and acoustic pollution data using about 50 sensors deployed in the city and installed in seven different urban areas. The number of components, frequency of measure, frequency of sending and updating information, and some other information details are presented in Table 4. The smart noise control solution implemented in Barcelona enables to optimize and centralize the collection, integration, processing, and dissemination of information by the noise sensors of different suppliers and sound level meters distributed throughout the city (Bibri and Krogstie 2020b).

As stated by Sinaeepourfard et al. (2016), air monitoring is part of urban lab monitoring management, which provides a variety of services related to the air, temperature, humidity, and other transportation issues. The active sensors recording the relative and appropriate information for the services are spread in the different zones of Barcelona for obtaining the accurate data for services. Table 5 presents only the data for the air quality. The sensors provide real-time information about the air quality in the city.

Table 5 Airmonitoring management

Type	Number of devices	Sending data (byte)		
		by each sensor at each transaction	by each sensor per day	Total amount of data per day
Air quality	40,000	144	13,824	552,960,000

Source: Adapted from Sinaeepourfard et al. (2016)

However, due to the challenges of enacting environmental monitoring, the collection of information of various types about the state of the environment does not guarantee a maximized effect of the use of this information. This opens up wide prospects for further developing environmental monitoring technologies and enhancing their applications in the future. The current challenge lies in the effective integration of multiple environmental data sources originating from different environmental networks and institutions, which requires specialized observation equipment, tools, techniques, and models to establish air pollutant concentrations at different spatial and temporal scales. Among the technologies implemented in Barcelona for environmental monitoring include: Community Multiscale Air Quality (CMAQ) modeling system, Real-time Air Quality Index (AQI), NMMB/BSC-Dust Forecast OMI (Ozone Monitoring Instrument), An Artificial Neural Network (ANN) to forecast PM10 daily concentration (Nikitin et al. 2016).

Smart urban metabolism: real-time feedback on energy flows tailored to various stakeholder groups

Urban metabolism (UM) as a model is used to understand the flows of the energy and materials through urban environments by facilitating their description and analysis. It provides researchers with a metaphorical framework to study the interactions of natural systems and human systems in specific districts, cities, or regions. It also provides a platform through which sustainability implications can be considered (Pincet et al. 2012). The term has been defined by Kennedy et al. (2007, p. 44) as "the total sum of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste." UM is the stocks and flows of energy and materials in cities and their relationship with urban infrastructure (Kennedy et al. 2012), However, sustainable (eco-) cities have tended to focus mainly on the underlying structure of UM—sewage, water, energy, and waste generation and management, thereby falling short in considering data-driven smart solutions (Bibri and Krogstie 2017a, 2019a). In fact, there are some limitations associated with the current UM framework, including high data and resource requirement, lack of follow-up and evaluation of the evolution of a city's UM, and difficulties in identifying the cause-and-effect relationships of the metabolic flows (Shahrokni et al. 2014b). Moreover, the application of this framework at the city level has been limited by the lack of data on energy and material flows at this scale (Broto et al. 2012; Kennedy et al. 2007; Weisz and Steinberger 2010), an issue which concern both production- and consumption-based approaches (Baynes and Wiedmann 2012). Therefore, the new smart urban metabolism (SUM) framework has recently gained more focus in research and practice. In the context of this paper, the SUM framework as an ICT-enabled evolution of UM has been developed to overcome those challenges as applied to the case of SRS (Shahrokni et al. 2015b). The key features of the new SUM framework are that (Shahrokni et al. 2015a, b) it is based on:

- the integration of high-quality (up to real-time), siloed, heterogenous data streams in urban environments;

- high temporal resolution in the sense of processing energy and material flows in a real-time calculation engine to provide real-time data on energy consumption, GHG emissions, water consumption, material consumption, and waste production;
- high spatial resolution in the sense of simultaneously providing the UM on several levels of urbanism, from the city down to the household; and
- the continuous illustration of energy and material flows to city officials, organizations, and citizens through real-time feedback (visualizations) tailored to each stakeholder level, from the household to the urban district.

Smart sustainable cities are increasingly utilizing urban dashboards in the operations and management tasks of their complex UM. These intelligent systems aid in monitoring the dynamics of the city, integrating numerous sensors and big data analysis technologies with the aim of optimizing the infrastructures and services of the city and maintaining its robustness. However, important to note is that the focus of this paper is on energy flows and related environmental issues. These flows, detailed in Table 6, are collected on the lowest level possible, starting at the household, then aggregated to the building level, and finally to the district level. Table 2 includes only local flows of energy related to electricity consumption, heating and cooling consumption, and on/site generation; fuel consumption; and on-side energy production as relevant to this paper.

Shahrokni et al. (2015b) present the first implementation of SUM in the Smart Eco-City SRS R&D project, and further analyze some challenges and barriers to this implementation and discuss the potential long-term implications of the findings. Four key performance indicators (KPIs) are generated in real time based on the integration of heterogeneous, real–time data sources, namely:

1. Kilowatt–hours per square meter
2. Carbon dioxide equivalents per capita
3. Kilowatt–hours of primary energy per capita
4. Share of renewables percentage.

Table 6 Data sources for energy for developing SUM: Adapted from Shahrokni et al. (2015a)

Local Flows	Data Points	Data Owners
Electricity, Heating Cooling, Water Use, On/Site Generation	Billing Meters, Submeters	Energy Utility, Building Owner, Homeowner
Transportation—Car, Public, Goods, Fuel Use	GPS, GSM, Road Tolls, Vehicle Registrations, Taxi Logistics, 3rd Party Apps, Surveys, Public Transit Logistics System, Traveler Card Swipes, Package Tracking Numbers, Road Tolls, Billing Systems	Car owner, Telco's, Transportation Authority, Taxi Companies, App Developer, Statistics Bureaus, Package Tracking Numbers, Road Tolls, Gasoline Station Billing Records
On-Site Carbon Sequestration	Municipal Tree Inventory, Carbon Sequestration Volume	Municipality, Energy Utility
Energy Production	Public Electricity Use (E.g. Parks), Public Transportation Electricity Use, EV Charging Electricity & Location, Electricity Generation Fuel Mix, Grid Failures, Peak Load Reduction, Local Heat/Cooling Production to the Grid	Energy Utility

These KPIs are fed back on three levels (household, building, and district) on four interfaces developed for different audiences. Table 7 provides an overview of current smart urban metabolism feedback metrics.

Speaking of performance indicators at the building and household levels, advanced ICT has made it easier to collect performance parameters from the built environment so to be able to carry out a detailed evaluation of energy consumption. Holmstedt et al. (2018) examine the potential of using dynamic and high resolution meter data for the evaluation of energy consumption in buildings and households in SRS. The novelty identified with this approach is that it can increase the level of detail in the evaluation results and ease the detection of deviations in the structures performance. However, most benefits are from the occupant perspective, as more detailed evaluation information enable better inclusion of this stakeholder group. The authors found that the commonly used indicator energy use per heated floor area remains an inadequate tool for communication when taking a holistic approach to building energy evaluation.

Furthermore, the prototype developed for SRS employs a hybrid approach to the implementation of the SUM concept, with the real-time calculation engine being able to process production and consumption data. This implementation includes three phases: (1) the aquisition of data, (2) the development of a calculation engine and data processing, and (3) the development of feedback tailored to individual stakeholder requirements. The current focus of the SRS prototype is to understand the GHG emissions resulting from the consumption of electricity, heat, water, and the production of waste in the SRS (Shahrokni et al. 2015a).

However, as with all advanced ICT-based solutions, there are several challenges, barriers, and issues that need to be addressed and overcome, just as there are opportunities that need to be embraced and explored. One of the challenging barriers identified by Shahrokni et al. (2015b) lies in accessing and integrating siloed data from the different data owners. There are some instances when some residents choose simply not to be involved in, or later opt out of, providing data due to privacy concerns. Adding to this is the technical issues related to emission factors, system boundaries, data structure, ontology, heterogeneous data, and multiple sensors tracking the same flow (Shahrokni and Brandt 2013). Also, Holmstedt et al. (2018) identify several limitations associated with using dynamic and high resolution meter data for the evaluation of energy consumption in buildings and households, namely data collection and management, preservation of personal integrity, and incentives to react to the given evaluation information.

Table 7 An overview of current SUM feedback metrics

Feedback indicator	*Urban level*	*In time (customizable)*	
Energy, kWh	Household level	Last hour	Capitaa
Primary energy, kWh	Building level	Last day	Area (heated area "Atemp")
CO2-eq, kg	Neighborhood level	Last week	Level average (e.g., 15% lower than average building)
% renewable energy	District level	Last month	

Nevertheless, the new SUM framework involves a number of long–term opportunities, including enabling a new understanding of the causalities that govern urbanism and allowing citizens and city officials to receive feedback on the consequences of their choices in a systematic way (Shahrokni et al. 2015b). Integrating and analyzing data from different city systems and domains to provide real-time feedback to such city stakeholders as planners, businesses, industries, organizations, institutions, and citizens can support decision making and generate new insights through making them aware of the effects of their actions. This is important to meet the vision of the real-time feedback as outlined in the city's sustainability program for SRS, which represents the joint collaboration effort of utilities, developers, citizens, as well as the departments of the city (Kramers et al. 2016).

Discussion

The results have shown that smart grids, smart meters, smart buildings, smart environmental monitoring, and smart urban metabolism are the main data-driven smart solutions applied for improving and advancing environmental sustainability in both eco-cities and smart cities. Such solutions are increasingly being implemented within sustainable cities as part of their sustainable energy systems and within smart cities as part of their smart energy systems. Smart grids are considered as the backbone or anchor of smart cities.

A number of studies on the overall relationship between ICT and climate change show that the positive effects of ICT on reducing GHG emissions result from increasing the efficiency and flexibility of energy production, distribution, and transmission (e.g., GeSI 2008; Griffiths 2008; ITU 2007; MacLean and Arnaud 2008; EEF 2008; EICTA 2009; Reding 2008), and such effects increase more significantly when energy efficiency is combined with renewable energy sources (WWF, Pamlin and Pahlman 2008). Renewables continue to scale faster than expected. According to Renewable Energy Policy Network for the 21st Century (REN21) (2010), renewable energy capacity grew at annual rates of 10–60% worldwide for many renewable technologies. The levelised cost of renewables has come down to the point where build-out (work done to make energy systems ready for use or to expand them) have become cheaper than fossil fuels coupled to carbon capture and storage technology. This puts the emphasis on how renewable energy should be integrated with the power grid system at scale, and what this requires in respect to storage solutions as well as mechanisms for decentralized energy generation, sharing, and sale.

Smart grid technologies provide numerous benefits associated with energy management, energy conservation, cost reduction, as well as the integration of alternative energy sources in power generation, transmission, and distribution systems in the context of smart cities and sustainable cities (e.g., Al Nuaimi et al. 2015; Bibri 2018b, 2019b, 2020a; Brown and Zhou 2012/2014, 2013; Brown 2014; Ersue et al. 2014; Hashem et al. 2016; Kumar and Prakash 2016; Mohamed and Al-Jaroodi 2014; Kyriazis et al. 2014; Parello et al. 2014; Yin et al. 2013). They allow bi-directional energy flows and information between suppliers and consumers and provide data on real time usage and energy pricing. This in turn provides numerous advantages, including real time visibility, service reliability, control of cost and electricity usage, shift in peak load, capacity requirement of the grid, and energy production and sharing (prosumer). Similarly, smart building technologies have proven to be effective in curbing energy consumption (e.g., Bibri 2018b; GeSI 2008; Kramers et al. 2014). They can provide a multifunctional role in energy efficiency and GHG emissions reductions through highly advanced automatic systems for efficient and natural lighting, temperature control, window and door operations, efficient electric appliances, and many other functions. BMS allows more efficient operation, keeps the building climate within a specified range, reduces energy consumption, decreases energy costs, and gurantees safety and security.

The different methods of collecting information about the air quality and the presence of different harmful substances in the air have undergone major advances thanks to the IoT and the associated sensor networks. These are able in real time to gather data about the air condition in different parts of the city and transmit these data via a wireless connection to special analytical centers for further processing and analysis. Moreover, it is possible now to produce a comprehensive analysis of the obtained data, which enables the city authorities to observe the condition of the air and then forecasts about its pollution on the basis of such analysis based on sophisticated modelling and simulation systems. This is to effectively build a variety of preventive systems for environmental protection and to inform citizens and other city stakeholders about GHG emissions. In this light, more and more technologies have recently been developed and implemented in Stockholm and Barcelona for the purpose of monitoring the environment and the timely implementation of preventive measures for its protection, as well as dealing with the problem of air pollution. The identified data-driven smart solutions for air pollution are complementary to those for energy efficiency. The latter are indeed intended to control GHG emissions. Smart environmental control systems in smart sustainable cities can help to collect critical information to make better policy decisions to reduce GHG emissions. Such systems can also guide citizens on making their own efforts for rediucing GHG emissions by a variety of means.

However, although the two cities do collect information of various types about the state of the environment, not all competent authorities have an idea about how to maximize the effect of the use of the collected data, which opens up wide prospects for advancing this technology in the future. Air quality monitoring is challenging to enact as it requires the effective integration of multiple environmental data sources, which often originate from different environmental networks and institutions (Rada et al. 2016). These challenges require specialized observation equipment and tools to establish air pollutant concentrations, including sensor networks, geographic information system (GIS) models, and the Sensor Observation Service (SOS), a web service for querying real-time sensor data (Rada et al. 2016).

The benefits of UM are numerous as to supporting the sustainable development of urban systems (Baccini 1997; Barles 2010; Minx et al. 2010) through a holistic analysis of energy and material pathways. This serves to conceive of management systems and technologies that allow for the reintegration of natural processes, increasing the efficiency of resource use, and the conservation of (and even production of) energy (Newman 1999). These are expected to undergo major transformations thanks to big data analytics. Indeed, advanced ICT has recently demonstrated high potential not only to overcome the limitations associated with UM, but also to provide sophisticated approaches to data collection and analysis under the new SUM framework. Big data technology can allow for radical increases in the speed and complexity of data processing and analysis. The associated solutions often contribute to strategies for decoupling environmental impact from urban development as to various dimensions of urbanization, increasingly achieved through the increase in efficiency enabled by the IoT and big data analytics. The development of data-driven smart solutions to improve the environmental sustainability of cities has been triggered by the co-development of advanced ICT and infrastructure systems. The increasing integration of the core enabling technologies of the IoT and big data analytics in smart sustainable cities, such as sensor networks, real-time heterogeneous data-sources, and data processing platforms, creates the possibilities of obtaining a better understanding of energy flows in urban environments. This can have several effects as to enhancing smart infrastructure systems to augment energy flows and communicate related information to achieve the environmental objectives of sustainable development by different city stakeholder using a number of communication tools and methods. These include sustainable human computer interaction (HCI) (DiSalvo et al. 2010), eco-visualization (Holmes 2007), augmented reality (Azuma et al. 2001), computers and smart phones (Townsend 2010; Zapico et al. 2009), persuasive technology (Fogg 2002), and climate pervasive services (Zapico et al. 2009). On the whole, the real-time data collection and analytics provides great opportunities for developing applications to use and visualize energy consumption and GHG emissions, directed for behavioral change, sustainable lifestyles, environmental stewardship, and so on.

Worth discussing moreover is that SUM is in line with the unprecedented paradigmatic and scholarly shifts that the many sciences underlying smart sustainable urbanism are undergoing in light of big data science and analytics (see Bibri 2019d for further details). This relates to what has been termed “the fourth paradigm of science,” a scientific revolution that is marked by both the emergence of big data science and analytics and the increasing adoption of the underlying technologies in scientific and scholarly research and social practices. Everything about knowledge production is fundamentally changing thanks to the fast-flowing torrent of big data. This is the primary fuel of the new age, which powerful computational processes algorithms are using to generate valuable knowledge for enhanced decision-making and deep insights pertaining to a wide variety of practical uses and applications. This is at the core of UM given its inherent quantitative nature. UM studies have been used to provide indicators for assessing urban sustainability and quantifying GHG emissions of cities, such as measures of energy consumption (Kennedy et al. 2011). UM is also applied to sustainable urban planning and design as well as policy analysis. These applications are categorized by Kennedy et al. (2011) into four main areas: sustainability indicators (e.g., information pertaining to energy efficiency, quantification of GHG emissions, dynamic mathematical models for policy analysis, and urban design). Generally, urban sustainability as entailing complex dynamics of human-natural system interactions requires a decisive, radical change in the way the science is undertaken and developed. This change is what data-intensive science—a data-driven exploration-centered form of science, where big data computing and the underpinning technologies are heavily used to help scientists and scholars to manage, analyze, and share data for multiple purposes—is about (Bibri 2019d). SUM is one of the transformations that is enabled by what data-intensive science is offering in terms of its novel computational and scientific approaches in the light of the nature of the shortcomings associated with the application of UM in the context of urban planning and design, including intensive data collection and analysis and a lack of data at the city scale.

Stockholm has the best practices for environmental sustainability given its high level of sustainable development practices, including the implementation of applied data-driven solutions and their integration with green energy technologies to reach environmental targets. This can further be demonstrated by the SUM solution that has been implemented in the Smart Eco-city District of SRS to monitor environmental sustainability outcomes concerning energy consumption and GHG emissions. SUM as a new framework is more associated with sustainable cities given their strong environmental policies than smart cities. The concept of UM is fundamental to the development of sustainable cities (Kennedy et al. 201; Niza et al. 2009). UM research "involves conceptualizing a city … as an organism and tracking resources that go into the system and products and wastes that leave it" (Bai 2007, p. 1). In the eco–city as defined by Register (2002) as an urban environmental system, input of resources and output of waste are minimized (Register 2002).

Nonetheless, while the two cities differ in the nature rather than the degree of the implementation of data-driven smart solutions as best reflected in their overall environmental performance, Barcelona as a smart city is taking concrete actions with respect to energy efficiency and pollution mitigation. Accordingly, the smart ecological/environmental ideal has succeeded in enabling action in major cities around the world, and has recently become normalized as a widely accepted set of consensus concepts and ideas related to the sustainable city (Bibri 2020a; Cowley 2016). Besides, the enabling, integrative, and ubiquity nature of the IoT and big data technologies supports and justifies their applicability to the different paradigms of urbanism within different contexts, irrespective of the complexity of the environmental, economic, and socio-political systems of the city.

In recent years, the IoT and big data technologies have become a central issue in the domain of smart sustainable urbanism. The generation of colossal amounts of data and the development of sophisticated data analytics techniques for monitoring, understanding, and analyzing urban systems are the most significant aspects of smart cities that are being embraced and leveraged by sustainable cities in the endeavor to enhance their contribution to sustainability (Bibri and Krogstie 2019a, b). While smart eco-cities generally deal with the challenges of environmental, economic, and social sustainability and prioritize strategies and solutions accordingly (see Bibri and Krogstie 2020a for a comprehensive case study), the environmental dimension of sustainability remains at the core of the eco-city(e.g., Bibri 2020b; Holmstedt et al. 2017; Mostafavi and Doherty 2010; Rapoport and Vernay 2011). As such, they involve the combination of ecological and compact strategies as well as smart solutions (e.g., Bibri and Krogstie 2020a, c; Höjer and Wangel 2015; Pandis and Brandt 2011; Späth 2017). Regarding the latter, the use of the IoT and big data analytics in ecological urbanism has just recently gained interest in research (e.g., Bibri 2018a, 2019a, 2020b; Bibri and Krogstie 2017b; Shahrokni et al. 2014a, b; Shahrokni et al. 2015a, b). As regards smart cities, while all of them face the same challenges of sustainability in the light of the escalating urbanization trend, they differ in the policies and strategies they adopt to deal with and overcome such challenges. Moreover, smart cities vary in the kind of challenges they face and the solutions they prioritize. Evertzen et al. (2018) provide some comparative insights into the key differences between several cities. Regardless, the challenges for achieving the goals they pursue have been brought to the forefront by the combination of the IoT and big data analytics in recent years.

The emerging data–driven smart solutions have become of paramount importance to smart sustainable urbanism in regard to city development planning and city operational management. A key aspect of this is the use of urban big data as the evidence base for formulating urban policies, plans, strategies, and programs themselves, as well as for tracking their effectiveness and modelling and simulating future urban development projects. The operation and organization of urban systems and the coordination of urban domains require not only the use of complex interdisciplinary knowledge, but also the application of sophisticated approaches and the use of powerful engineering solutions underpinned by advanced computational analytics (e.g., Batty 2013, Batty et al. 2012; Bibri 2019a, d, e, 2020a, b; Bibri and Krogstie 2017c, 2018; Bibri et al. 2020; Bettencourt 2014; Kitchin 2014). Modern cities employ the latest technologies in city development planning and city operational management to support sustainable development given rapid urban growth, increasing urban domains, and more complex infrastructures. The use of big data provides the basis for cities to be more sustainable, efficient, resilient, equitable, and livable.

Conclusion

Data-driven technologies have become essential to the functioning of smart sustainable cities, particularly in relation to their contribution to environmental sustainability. This paper investigated the potential and role of data-driven smart solutions in improving and advancing environmental sustainability in the context of smart cities as well as sustainable cities under what can be labeled "environmentally data-driven smart sustainable cities." This study has shown that smart grids, smart meters, smart buildings, smart environmental monitoring, and smart urban metabolism are the main data-driven smart solutions applied for improving and advancing environmental sustainability in both eco-cities and smart cities. There is a clear synergy between such solutions in terms of their interaction or cooperation to produce combined effects greater than the sum of their separate effects—with respect to the environment. This involves energy efficiency improvement, environmental pollution reduction, renewable energy adoption, and real-time feedback on energy flows, with high temporal and spatial resolutions.

Every city has its specific opportunities, capabilities, and constraints, not least in relation to the application of advanced technologies for environmental sustainability. Hence, there are many things for cities to learn from each other concerning the knowledge and expertise they can demonstrate in this regard. It is therefore crucial to investigate the innovative solutions and sustainable strategies of different cities based on the ongoing and future projects and initiatives in their local context for learning purposes. Especially, it is well understood that there cannot be a set of rigid strategic guidelines that should be strictly followed and implemented anywhere around the world to achieve environmental sustainability. Sustainability generally depends on several intertwined factors that should fit the local context. In view of that, each city should tap into its local opportunities and capabilities as well as assesses its constraints and potentials from a more integrated perspective given the complexity surrounding the socio-political systems of the city. Overall, smart sustainable urbanism is shaped by socio–cultural and politico–institutional structures.

There is much enthusiasm currently about the opportunities created by the big data deluge and its new and more extensive sources in the domain of smart sustainable urbanism. This involves, in the context of SUM, the collection, processing, and analysis of energy flows to provide data on, among others, energy consumption and GHG emissions based on high temporal and spatial resolutions. The analytical outcome can be used in planning to follow up on the environmental goals of sustainability by optimizing energy efficiency with respect to utilities and building owners, as well as by mitigating the environmental impacts of energy consumption in regard to households thanks to the user-generated automated data collection, real-time analytics, and tailored feedback to various stakeholders needs.

The prospect of real–time data collection and analysis at any instant will provide the opportunity for aggregating and harnessing urban data to deal with urban changes at any scale and over any time period. Currently, datasets are able to show the real-time functioning of energy systems and provide deep insights into how long term environmental changes can be detected. Short–termism in energy planning is about measuring, evaluating, modelling, and simulating what takes place over hours, days, or weeks instead of months, years, or decades. In this respect, big data analytics can be used to derive new theories of how urban systems function, energy consumption increases, and GHG emissions rise in ways that focus on much shorter term issues than hitherto to contain the negative impacts of energy use on the environment. In addition, continuous energy planning as data constantly flood from urban systems in operation and are updated in real time allows for a dynamic conception of planning in response to the processual outcomes of urbanization as regards living and consuming processes. Especially, the data-driven smart solutions pertaining to urban metabolism, which include smart grids as part of energy production flows, derive a real-time dynamic understanding of energy flows, which can provide planners a good basis for decision-making as to the system consequences of their decisions and actions on the environment. They moreover enable the further optimization of energy efficiency through automated decisions. In a nutshell, as concluded by Bibri (2019f), smart sustainable urbanism will prevail for many years yet to come given the underlying transformational power of big data science and analytics, coupled with its legitimation capacity associated with the scientific discourse as the ultimate form of rational thought and the basis for legitimacy in knowledge production.

The present study offers insights that can inform future research agendas on smart sustainable urbanism from a technological and environmental perspective. More specifically, it provides the grounding for further in–depth research on the untapped potential of the IoT and big data technologies and their novel applications in advancing and improving environmental sustainability in the context of smart sustainable cities of the future. We would particularly like to encourage research on the development of a holistic approach to environmental sustainability underpinned by a strong synergy and dynamic interplay between techno-scientific and socio-political dimensions for the primary purpose of devising more effective solutions and more concrete guidelines and clear pathways for a wider implementation. This is predicated on the assumption that the data-driven smart solutions applied do not exist independently of the instruments, systems, practices, and knowledge employed and embedded within the multidimensional context (e.g., local, national, social, political, cultural, institutional, organizational, regulatory, etc.)—where they are created and disseminated. Also, we would like to draw the attention of future researchers to the importance of developing a deeper understanding of the multi–faceted processes of change to achieve environment sustainability in the era of big data revolution through focused discursive investigations on, and practical implementations of, data-driven smart solutions in different contexts. Moreover, qualitative analyses of the kind that we have attempted, which try to illuminate how the data-driven smart solutions contribute to SDG 7 is of high importance and value. One key reason for this is that as the demand for practical ideas from both the technologically and ecologically advanced nations about how to achieve the environmental objectives of sustainable development through emerging technologies, such solutions are likely to get increasing attention from the policy makers and practitioners from other major cities around the world. Further research should focus on providing the knowledge that these actors will need to make informed decisions about how to achieve those objectives through the development and implementation of the solutions in question in their own context. In addition, as this study has demonstrated that solutions for improving and advancing environmental sustainability already exist and are rapidly evolving across the selected cities, it would be useful and worthy to pursue a wider and more varied comparison (involving cities from other European and Scandinavian countries or from other parts of the world) with a view to revealing more global trends in smart sustainable urbanism. Taking up this in future research is indeed justified by the limitations to the present study, which pertain to the case selection that included only European countries. Due to this bias in the case selection, it is moreover conceivable that potentially more data-driven smart solutions for environmental sustainability exist in other cities in Europe and around the world.

Finally, the concepts, ideas, and findings presented in this study for policy makers provide practical clues as well as lessons on the expected benefits of developing and implementing data-driven smart solutions to accelerate the movement towards environmental sustainability in the light of the emerging paradigm of the IoT and big data computing. Most of the time, when it comes to data-driven smart sustainable urbanism, contradictions, uncertainties, and even contentions and conflicts emerge during the cooperation and interaction between policymakers, planners, government officials, sustainability strategists, urban scientists, ICT experts, environmental engineers, technologists, industry experts, thought leaders, and citizens, irrespective of whether the city is already badging or just regenerating itself as data-driven smart sustainable. This phenomenon is nevertheless common in all urban development projects and initiatives due to the difficulty of aligning and accommodating the various interests and expectations of the involved city stakeholders. Regardless, learning from the experience and knowledge of the leading cities in their areas of expertise is a common way to formulate and implement urban visions, policies, and strategies through drawing positive and negative lessons and acting about the outcome We hope to have contributed our share to improving that practice.

Abbreviations

AMI: Automated Meter Infrastructure; ANN: Artificial Neural Network; AQI: Real-time Air Quality Index; BAS: Building Automation System; BDIS: Big Data Infrastructure Services; BDPS: Big Data Platform Services; BDAS: Big Data Analytics

Services; BMS: Building Management System; CityOS: City Operating System; CMAQ: Community Multiscale Air Quality; DSM: Demand Side Management; EVs: Electric Vehicles; GHG: Greenhouse Gases; HVAC: Heating, Ventilation, and Air Conditioning; ICT: Information and Communication Technology; IoT: Internet of Things; KPIs: Key Performance Indicators; NFC: Near-field Communication; OMI: Ozone Monitoring Instrument; RFID: Radio Frequency Identification; SDG: Sustainable Development Goal; SOS: Sensor Observation Service; GIS: Geographical Information System; SRS: Stockholm Royal Seaport; SUM: Smart Urban Metabolism; UM: Urban Metabolism

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Data-Driven Smart Sustainable Cities of the Future: A Novel Model of Urbanism and its Core Dimensions, Strategies, and Solutions

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Article

Data-Driven Smart Sustainable Cities of the Future: A Novel Model of Urbanism and Its Core Dimensions, Strategies, and Solutions

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Abstract

The big data revolution is heralding an era where instrumentation, datafication, and computation are increasingly pervading the very fabric of cities. Big data technologies are seen as a powerful force that has great potential for improving and advancing urban sustainability thanks especially to the IoT. Therefore, they have become essential to the functioning of sustainable cities. Besides, yet knowing to what extent we are actually making any progress towards sustainable cities remains problematic, adding to the conflicting, or at least fragmented, picture that arises of change on the ground in the light of the escalating urbanization trend. In a nutshell, new circumstances require new responses. One of these responses that has recently gained prevalence worldwide is the idea of "data-driven smart sustainable cities." This paper sets out to identify and integrate the underlying components of a novel model for data-driven smart sustainable cities of the future. This entails amalgamating the prevailing and emerging paradigms of urbanism in terms of their strategies and solutions, namely compact cities, eco-cities, data–driven smart cities, and environmentally data-driven smart sustainable cities. This amalgamation is grounded in the outcomes of the four case studies conducted on six of the ecologically and technologically leading cities in Europe. This empirical research is part of an extensive futures study, which aims to analyze, investigate, and develop a novel model for data-driven smart sustainable cities of the future using backcasting as a strategic planning process. We argue that the proposed model has great potential to improve and advance the contribution of sustainable cities to the goals of sustainability by harnessing its synergistic effects thanks to data-driven technologies and solutions. This new model is believed to be the first of its kind and thus has not been, to the best of our knowledge, produced, nor is it currently under investigation, elsewhere.

Keywords

Data-Driven Smart Sustainable Cities, Sustainable Cities, Compact Cities, Eco–Cities, Data–Driven Smart Cities, Urbanism, Backcasting, Planning, Big Data Technology

Introduction

Cities have a defining role in strategic sustainable development. Therefore, they have gained a central position in operationalizing the notion and applying the discourse of sustainable development. This is clearly reflected in the Sustainable Development Goal 11 (SGD 11) of the United Nations' 2030 Agenda, which entails making cities more sustainable, resilient, inclusive, and safe (UN, 2015a). In this respect, the UN's 2030 Agenda regards ICT as a means to promote socio–economic development and protect the environment, increase resource efficiency, achieve human progress and knowledge in societies, upgrade legacy infrastructure, and retrofit industries based on sustainable design principles (UN, 2015b). Therefore, the multifaceted potential of the smart city approach as enabled by advanced ICT has been under investigation by the UN (2015c) through their study on 'Big Data and the 2030 Agenda for Sustainable Development.' Besides, the world is drowning in data—and if planners and policymakers realize the untapped potential of leveraging these data in collaboration with urban scientists and data scientists, the outcome could solve major problems and challenges facing modern cities.

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Sustainable cities have been the leading global paradigm of urbanism (Bibri, 2019a, 2020a; Williams, 2010) for over four decades thanks to the models of sustainable urban form proposed as new frameworks for restructuring and redesigning urban places to make urban living sustainable, especially compact cities and eco-cities. These forms of human settlements continue to strive towards reaching the optimal level of sustainability and to enable the built environment to function in ways that reduce material use, lower energy consumption, mitigate pollution, and minimize waste, as well as improve social equity and human well–being (Bibri & Krogstie, 2017a, 2017b). Indeed, a number of recent United Nations reports and policy papers argue that the compact city and the eco–city as the central paradigms of sustainable urbanism have positive effects on resource efficiency, climate change, economic development, social integration and cohesion, citizen health and quality of life, and cultural dynamics (Bibri, 2020a, 2020b, 2020c; Hofstad, 2012; Jabareen, 2006; Joss, Cowley, & Tomozeiu, 2013; Lim, & Kain, 2016). In short, sustainable urbanism is promoted by global, national, and local policies as the most preferred response to the challenges of sustainable development. It is argued that the compact city strategies are able to achieve all of the benefits of sustainability (Bibri, Krogstie, & Kärrholm, 2020; Burton, 2002; Dempsey, 2010; Hofstad, 2012; Jenks & Jones, 2010), and that the eco–city strategies are able to provide healthy and livable human environments in conjunction with minimal demand on resources and thus minimal environmental impacts (Bibri & Krogstie, 2020a; Mostafavi & Doherty, 2010; Iverot & Brandt, 2011; Rapoport & Vernay, 2011).

The change is still inspiring and the challenge continues to induce scholars, practitioners, and policymakers to enhance the existing models of sustainable urban form, or to propose new integrated models in response to the global shifts at play today, notably the rise of ICT and the spread of urbanization. Indeed, in the current climate of the escalating urbanization and increasing uncertainty of the world, it may be more challenging for sustainable cities to reconfigure themselves more sustainably without the use of advanced technologies. In addition, the issue of sustainable cities has been problematic, whether in theory or practice (Bibri & Krogstie, 2017a, 2019a, 2019b), so too knowing to what extent we are actually making any progress towards urban sustainability. Hence, much more needs to be done considering the very fragmented picture that arises of change on the ground in the light of the expanding trend of urbanization. In this respect, it has been suggested that sustainable cities need to embrace and leverage what advanced ICT has to offer so as to improve, advance, and maintain their contribution to sustainability (e.g., Bibri & Krogstie, 2017a, 2017b; Höjer & Wangel, 2015).

Against the backdrop of the complex challenges of sustainability and urbanization, a number of alternative and new ways of planning, designing, managing, and governing cities based on advanced ICT have materialized and are rapidly evolving, paving the way for sustainable cities to optimize and enhance their performance with respect to sustainability. There is an increasing recognition that advanced ICT constitutes a promising response to the challenges of sustainability and urbanization due to its tremendous, yet untapped, potential for solving many socio–economic and environmental problems and issues. Both sustainable urbanism and smart urbanism approaches emphasize particularly the role of big data technologies and their novel applications as an advanced form of ICT in improving sustainability. This trend has been demonstrated by many studies conducted in recent years (e.g., Bettencourt, 2014; Bibri, 2018a, 2018b, 2019a, 2019b, 2020a, 2020b, 2020c; Bibri & Krogstie, 2020a, 2020b, 2020c; Nikitin, Lantsev, Nugaev, & Yakovleva, 2016; Shahrokni, Levihn, & Brandt, 2014; Shahrokni, Lazarevic, & Brandt, 2014; Shahrokni, van der Heijde, Lazarevic, & Brandt, 2014).

A new era is presently unfolding wherein both sustainable urbanism and smart urbanism practices are being highly responsive to a form of data-driven urbanism. In light of this, there has recently been a conscious push for sustainable cities across the globe to be smarter and thus more sustainable by developing and implementing data-driven technology solutions in relation to various urban systems and domains to enhance and optimize their operations, functions, services, designs, strategies, and policies. Big data technologies have, in the context of sustainability, become as essential to the functioning of smart cities (e.g., Al Nuaimi, Al Neyadi, Nader, & Al-Jaroodi, 2015; Bibri, 2019c; Bibri & Krogstie, 2020b, 2020c; Bettencourt, 2014; Nikitin et al., 2016). as to that of sustainable cities (Bibri, 2018b, 2019b, 2020b; Bibri & Krogstie, 2018, 2019a, 2019b, 2020a, 2020b; Pasichnyi, Levihn, Shahrokni, Wallin, & Kordas, 2019; Shahrokni et al., 2014; Shahrokni, Levihn, & Brandt, 2014; Shahrokni et al., 2014; Shahrokni, Årman, Lazarevic, Nilsson, & Brandt, 2015; Shahrokni, Lazarevic, & Brandt, 2015). Consequently, we are moving into an era where instrumentation, datafication, and computation are routinely pervading the very fabric of both sustainable cities and smart cities. Modern cities employ the latest technologies to support sustainable development, notably the IoT and big data analytics.

Science-based technology is well aligned with the project of envisioning alternative futures. Advances in science and technology inevitably bring with them wide–ranging common visions on how cities will evolve in the future, as well as the opportunities and risks this future will bring (Bibri & Krogstie, 2016). At the beginning of a new decade, we have the opportunity to look forward and consider what we could achieve in the coming years in the era of big data. Again, we have the chance to consider the desirable futures of data–driven smart sustainable cities to our collective advantage. We are in the midst of an expansion of time horizons in sustainability planning in an urban world which is as much dominated by information flows as material flows. Sustainable cities look further into the future when forming strategies, and the movement towards a long–term vision arises from the three major mega trends that are shaping our society at a growing pace, namely sustainability, urbanization, and ICT. In recognizing a link between these trends, sustainable cities across the globe have adopted ambitious goals that extend far into the future and have developed different strategies to achieve these goals.

The aim of this paper is to identify and integrate the underlying components of a novel model for data-driven smart sustainable cities of the future. In doing so, it endeavors to amalgamate the prevailing and emerging paradigms of urbanism in terms of their strategies and solutions. This amalgamation is grounded in the outcomes of the four case studies conducted on six of the ecologically and technologically leading cities in Europe within the frameworks of compact cities, eco-cities, data–driven smart cities, and environmentally data-driven smart sustainable cities, this empirical research is part of an extensive backcasting-oriented futures study, which aims to analyze, investigate, and develop a novel model for data-driven smart sustainable cities of the future.

The futures study consists of six steps in total, each with several guiding questions to answer. The answer to the guiding questions for each step may involve one or more papers. This paper follows the earlier papers with Steps 1 and 2 (Bibri & Krogstie, 2019a), Step 3 (Bibri & Krogstie, 2019b), and Step 4 (Bibri, Krogstie, & Kärrholm, 2020; Bibri & Krogstie, 2020a, 2020b, 2020c). This paper answers Questions 1 and 2 of Step 5, namely:

1. What urban and technological components are necessary for the future model of urbanism?
2. How can all these components be integrated into a framework for strategic sustainable urban development planning?

The remainder of this paper is structured as follows. Section 2 focuses on the backcasting and case study approaches and their integration. Section 3 specifies the underlying urban and technological components of the novel model for data-driven smart sustainable cities of the future. Section 4 proposes, describes, and illustrates a novel framework for strategic sustainable urban development planning. This paper ends, in Section 5, with concluding remarks.

Research Methodology

The futures study applies a methodological framework which integrates a set of principles underlying several normative backcasting approaches as well as descriptive case study design for strategic urban planning whose core objective is clarifying which city model is desired and working towards that goal. Bibri (2020d) dedicates a whole article to the methodological framework applied in the futures study.

Integrating backcasting and case study approaches: Relevance and appropriateness

The backcasting approach was employed to achieve the overall aim of the futures study. The case study approach, which is associated with the empirical phase of the futures study, was used to examine and compare two of a total of six cases in each of the four case studies conducted: (1) Gothenburg and Helsingborg as compact cities (Bibri, Krogstie, & Kärrholm, 2020), (2) Stockholm and Malmö as eco-cities (Bibri & Krogstie, 2020a), (3) London and Barcelona as data–driven smart cities (Bibri & Krogstie, 2020b), and (4) Stockholm and Barcelona as environmentally data-driven smart sustainable cities (Bibri & Krogstie, 2020c). One important use of the case study approach in research is planning, which in turn is at the core of the backcasting approach. One of the essential requisites for employing the case study approach stems from one's motivation to illuminate complex phenomena (Merriam, 2009; Stake, 2006; Yin, 2017). Our motivation is to integrate the prevailing and emerging paradigms of urbanism in terms of their strategies and solutions.

The results of the case studies performed are intended to guide and inform the futures study in terms of identifying and integrating the underlying components of the novel model for data-driven smart sustainable cities of the future.

In specific terms, the investigation of the six cases selected is meant to identify the design strategies of sustainable cities and the data-driven solutions of smart cities that are needed to develop the city of the future as a new paradigm of urbanism. By carefully studying any unit of a certain universe, we are in terms of knowing some general aspects of it, at least a perspective that guides subsequent research (Wieviorka, 1992). Case studies often represent the first scholarly toe in the water in the new areas of research.

The case study and backcasting approaches are both regarded as a tool with which theories can be supported and their effects can be demonstrated, as well as facts can be developed. The purpose of analyzing and evaluating the six cases associated with the futures study is to provide the theoretical and practical foundations necessary for backcasting the future phenomenon of data-driven smart sustainable cities. In this respect, it is important first and foremost to define which characteristics of the future state of this phenomenon are meaningful, beneficial, and interesting, and should therefore be incorporated in the backcasting. This involves both the theoretical underpinnings and the emerging practices that are of pertinence and importance as a basis for the backcasting. With respect to the former, the material needed to make the backcasting depends on how strong the theoretical frameworks we have about the envisioned phenomenon of data-driven smart sustainable cities and their internal relationships from a conceptual, disciplinary, and discursive perspective (see Bibri, 2018a, 2018d, 2019a, 2019d, 2020a; Bibri & Krogstie, 2016, 2017c for further details). Commonly, quite a strong basis for backcasting any future phenomenon is available when there are frameworks that can explain, support, and justify that phenomenon.

Backcasting: A Strategic Planning Process

Backcasting works through envisioning and analyzing sustainable futures and then developing strategies and pathways to get there. Once the future desired conditions are imagined and articulated, the necessary steps are defined and pursued to attain those conditions. Backcasting is the process of generating a desirable future and then looking backwards to the present to determine the strategic actions needed to reach that specified future (Fig. 1). The first part of the process concerns the normative side of backcasting and the second part pertains to the analytical side of backcasting: both the possible ways of reaching certain futures as well as their feasibility and potential. Dreborg (1996) relates backcasting to Constructive Technology Assessment (CTA). The purpose of CTA is to broaden the technology development processes and the debate about technology with environmental and social aspects, as well as to enhance the participation of social actors. A distinction can be drawn between the analytical side and the constructive and process-oriented side of backcasting (Dreborg, 1996). With respect to the analytical side, the main result of backcasting studies are alternative images of the future, thoroughly analyzed in terms of their feasibility and consequences. Concerning the constructive-oriented side, backcasting studies should provide an input to a policy developing process in which relevant actors should be involved.

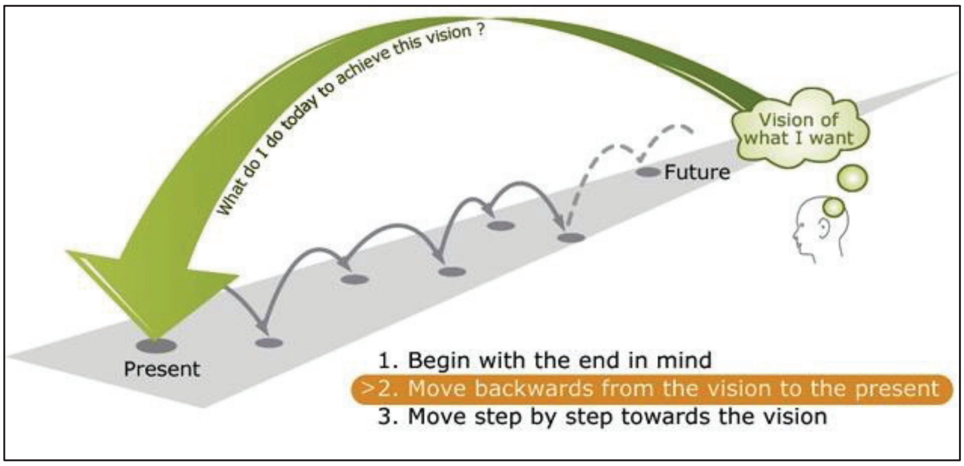

Fig. 1: The backcasting process from the Natural Step Source: Holmberg (1998)

Backwards-Looking Analysis: A Pathway-Oriented Category

The development of strategies and pathways to the future has long been the subject of futures studies, especially through the construction of futures visions to achieve the goals of sustainability. Typically, backcasting defines criteria for a desirable future and builds a feasible and logical path between the state of the future and the present. The latter allows to set priorities, develop alternative solutions, and determine the strategic actions that need to be taken in order to reach a desirable future. This relates, in the context of this paper, to the backwards-looking analysis (Step 6) of the backcasting study, which is concerned with developing strategies and pathways to a single desirable future.

There are several categories of backcasting. Wangel (2011) classifies backcasting into target-oriented backcasting (what can change); pathway-oriented backcasting (how to change); action-oriented backcasting (who could make change happen); and participation-oriented backcasting (to enhance participation and buy-in by stakeholders). The futures study is concerned with the pathway-oriented backcasting category where the focus is on how the changes can take place and the measures that support those changes. In this category, the setting of strict goals is considered less important (Vergragt & Quist, 2011; Wangel, 2011) compared to other categories. The pathway-oriented category of backcasting usually helps identify critical non-technical triggering measures. This is at the core of Step 6 of the futures study, which involves developing a series of planning measures and actions pertaining to urban design strategies, data-driven technology solutions, and sustainability targets and objectives that could be implemented in the near future. Accordingly, in the quest for the answer to how to reach the future vision, the strategies and pathways developed are intended to link goals which may lie far ahead in the future to some decisive steps which are to be designed and taken now to achieve those goals.

The Guiding Questions for the Six Steps in the Backcasting-oriented Futures Study

The literature shows that there are a number of backcasting methodologies and approaches applied in futures studies. While these differ in their steps and thus guiding questions, they tend to share the essentials. This implies that the backcasting framework is adaptive in nature based on the specific context under which it is applied. In this light, Bibri (2018c) synthesizes a backcasting approach to smart sustainable city development planning based on the review of a number of futures studies using different backcasting methodologies and approaches, and then later, Bibri (2020a) tailored it to the requirements of the future vision (see Table 1).

Table 1: The guiding questions for each step in the backcasting-oriented futures study

The guiding questions for the backcasting study	Methods and tools
Step 1: Detail strategic problem orientation (Part 1) 1. What is the model of urbanism to be studied? 2. What are the aim, purpose, and objectives of the backcasting study in relation to this model? 3. What are the long–term targets declared by the goal–oriented backcasting approach? 4. What are the objectives these targets are translated to for backcasting analysis?	Research design and problem formulation
Step 2: Detail strategic problem orientation (Part 2) 1. What are the main prevailing trends and expected developments related to the model to be studied? 2. What are the key sustainability problems associated with the current model of urbanism and what are the causes? 3. How is the problem defined?	Trend analysis and problem analysis
Step 3: Generate a sustainable future vision 1. What are the demands for the future vision? 2. How does the future model of urbanism look like? 3. How is the future model of urbanism different from the current model of urbanism? 4. What is the rationale for developing the future model of urbanism? 5. Which sustainability problems have been solved and which technologies have been used in the future vision?	Creativity method

The guiding questions for the backcasting study	Methods and tools
Step 4: Conduct empirical research 1. What is the justification for the methodological framework to be adopted? 2. Which category of case study design is most relevant to investigating the dimensions of the future model of urbanism? 3. How many case studies are to be carried out and what kind of urban phenomena should they illuminate? 4. To what extent can this investigation generate new ideas and illustrate the theories applied and their effects, as well as underpin and increase the feasibility of the future vision?	Case study method
Step 5: Specify and Integrate the components of the future model of urbanism 1. What urban and technological components are necessary for the future model of urbanism? 2. How can all these components be integrated into a framework for strategic sustainable urban development planning? 3. What are the benefits, potentials, and opportunities of the future model of urbanism?	Creativity method
Step 6: Perform backwards–looking analysis 1. What built infrastructure changes are necessary for achieving the future vision? 2. What essential urban infrastructure changes are necessary? 3. What technology infrastructure changes are necessary? 4. What social infrastructure changes are necessary? 5. What institutional and regulatory changes are necessary?	Backcasting analysis

The Time Horizon in Backcasting-Oriented Futures Studies

A typical time horizon used in many backcasting-oriented futures studies is 50 years. This time horizon is appealing because it is both realistic and far enough away to allow major changes and even disruptions in technologies and cultural norms and values. There also is a large body of work on backcasting that takes the perspective of 25-50 years as a time horizon. The futures study follows this perspective by covering the time period from 2020-2050, the time reasonably needed to develop a data-driven smart sustainable city as a desirable future. The rationale for this is that the future model of urbanism concerns particularly, but not only, those cities that are badging or regenerating themselves as sustainable, where, for example, some sustainable energy and waste systems, dense and diverse urban patterns, sustainable transportation infrastructure, green areas and parks, and technological infrastructure are already in place. And as they move towards 2050, a number of decisive steps will be taken along the way to reach the optimal level of sustainability with support of emerging and future ICT. And what this entails in terms of developing and implementing the IoT and big data technologies and their novel applications and establishing the associated technical and institutional competences on a wider scale.

However, the futures study is not setting out a fixed timeframe as the future is unknown and the world is uncertain, and the implication of this is that it can still take longer for sustainable cities to get closer to or reach the final destination. Not to mention those cities that are in the process of regenerating themselves as, or manifestly planning to become, sustainable and then smart sustainable. Worth pointing out is that the time horizon of 25-50 years associated with future visions as an evolutionary process is a basic principle to allow the planning and policy actions to pursue the path towards a more sustainable future. Backcasting is most relevant when the future is uncertain and our actions are likely to influence, inspire, or, ideally, create that future.

The Underlying Components of a Novel Model for Data-driven Smart Sustainable Cities of the Future

Urban components

In this section, we provide the answers to the first question of Step 5 of the futures study. The answer to this question is presented in Table 2, Table 3, and Table 4. These are distilled from the results of the four case studies conducted on (1) Gothenburg and Helsingborg as compact cities (Bibri, Krogstie, & Kärrholm, 2020), (2) Stockholm and Malmö as eco-cities (Bibri & Krogstie, 2020a), (3) London and Barcelona as data–driven smart cities (Bibri & Krogstie, 2020b), and (4) Stockholm and Barcelona as environmentally data-driven smart sustainable cities (Bibri

& Krogstie, 2020c).

The compact city model offers environmentally sound, socially beneficial, and economically viable development through highly dense and multidimensional mixed use patterns that rely on sustainable transportation and favor green space (Bibri, Krogstie, & Kärrholm, 2020). As such, it can be viewed as an all–encompassing understanding of urban complexities as well as an all-embracing conception of planning practices and strategies for achieving sustainability. The compact city model is justified by its ability to contribute to, and even support the balancing of, the environmental, economic, and social goals of sustainable development (Table 2).

Table 2: The design criteria and strategies of the compact city for achieving the goals of sustainability

Design Criteria	Strategies for Environmental, Economic, and Social Sustainability
Compactness	• Build and develop centrally • Concentrate around strategic nodes • Complement and mix • Reserve outer city areas for future development
Density	• High density of built objects in designed and emergent compact urban form • Diverse scales of built objects • Distribution of building footprints with frequent larger buildings • Greater density in strategic nodes • Prioritization of density close to the central points of strategic nodes • High–density hand in hand with multidimensional mixed land use
Mixed Land Use	• Physical land use mix (horizontal/spread of facilities, vertical mix of uses, amenity, public space, etc.) • Economic mix (business activity, production, consumption, etc.) • Social mix (housing, demography, lifestyles, visitors, etc.) • Greater mix of housing, business, and facilities in strategic nodes • Multidimensional mixed land use hand in hand with sustainable transportation
Sustainable Transportation	• Cycling and walking • Public transport (metro, buses, tram, etc.) • Mobility management • Increased accessibility through public transport infrastructure improvements • Sustainable transportation hand in hand with multidimensional mixed land use and high density • Network structure of link areas to connect the major nodes of the transport system • Separate lanes for the public transport for faster journey time and a punctual and reliable system • More services along the main corridors for greater frequency • An easy to understand, safe, and secure system for guaranteeing quality and service • Multi-model travelling in strategic nodes to support their dense and diverse central points
Green Structure	• Green areas and parks • Green areas hand in hand with density • Protection and integration of natural, agricultural and cultural areas through intensification
Intensification	• Increase in population • Increase in redevelopment of previously developed sites, subdivisions and conversions, and additions and extensions • Increase in development of previously undeveloped urban land • Increase in density and diversity of sub-centers • Investment in and improvement of transport infrastructure and services

The eco–city model delivers positive outcomes in terms of providing healthy and livable human environments in conjunction with minimal demand on resources and minimal impact on the environment. It involves mainly eco-design principles and technology solutions, supported by behavioral change, for achieving the goals of sustainability (Bibri & Krogstie, 2020a). Design encompasses greening, passive solar houses, sustainable transportation, mixed land use, and diversity. And technology comprises green energy systems, energy efficiency systems, and sustainable waste management systems. Design contributes to the three goals of sustainability, and technology contributes mostly to the environmental and economic goals of sustainability. Behavioral change is associated with sustainable travel, waste separation, and energy consumption.

Table 3: The design and technology strategies and solutions of the eco-city for achieving the goals of sustainability

Design and Technology Criteria	Eco-city Strategies for Environmental, Economic, and Social Sustainability
Environmental Sustainability	
Sustainable energy systems	• 100% locally generated renewable energy—sun, wind, and water • Local production of electricity—solar energy • Passive, low-energy, and net-zero buildings/houses • Bio–fueled CHP system
Sustainable waste management	• Convenient and smart waste collecting system • Vacuum waste chutes • Food waste disposers • Wastewater and sewage treatment system • Biological waste separation procedures • Biogas digesters • Behavioral change
Sustainable materials	• High performance materials • Resource–efficient (recycled and reused) materials • Minimized building waste • Pollution prevention
Sustainable transportation	• Cycling and walking • Public transport (metro, buses, tram, etc.) • Car pools (biogas and electric) • Private cars (biogas and electric) • Mobility management • Smart transport management • Smart traffic management • Behavioral change
Green and blue infrastructure	• Greening • Rainwater harvesting • Ecological diversity • Biodiversity • Green factor supplemented with green points • Green parks • Green streets and alleys • Green roofs • Rain gardens • Bioswales • Permeable Pavements

Economic Sustainability	
Mixed Land Use	• Physical land use mix (vertical and horizontal, amenities, facilities, public spaces, etc.) • Economic mix (business activity, production, consumption, etc.) • Some aspects of social mix (housing, demography, lifestyles, visitors, etc.)
Economic growth and business development	• Green–tech innovation • Green-tech production and export • R&D activities • Entrepreneurial and innovation-based startups • Industrial and technological investment • Job creation and skill development • Government, industry, and academia collaboration • International cooperation
Social Sustainability	
Social equity	• Reduction of social segregation and socio-economic disparity • Flexible design of housing in terms of tenures and forms • Affordable housing for all by means of an efficient, careful process • Equal access to public services
The quality of life	• Meeting places for social interaction • Ready access to facilities, public spaces, as well as recreational areas • Natural surveillance: safety and security • Housing design enabling residents to remain throughout all stages of life
Citizen participation	• Citizen involvement and consultation • Citizenship plurality consolidation • Citizen empowerment for community engagement and co-creation • Multi–stakeholder cooperation

Technological Components

The data–driven smart city solutions deliver positive outcomes in terms of responding to the challenges of sustainable development thanks to data–analytic thinking and how it can be utilized and practiced to enhance decision–making and to generate deep insights pertaining to a wide variety of practical uses and applications in the context of sustainability. Findings indicate that the leading data-driven smart cities in Europe are characterized by the following dimensions (Bibri & Krogstie, 2020b):

- High degree of the readiness of the city administration to the integration of advanced technology in the city management:
  - High availability and development level of the ICT infrastructure and big data analytics competencies required for the functioning of the city
  - New and extensive sources of data and high level of open data support
- High degree of the implementation of applied technology solutions for the city management:
  - High level of the development of applied data-driven solutions for city operational management and city development planning in the domain of sustainability
  - Established data-oriented competences pertaining to education, training, research, innovation, and strategic planning and policy

Table 4 provides a summary of the data-driven smart city solutions for sustainability: (a) technologies and (b) competences.

Table 4 (a): A summary of the data-driven smart city solutions for sustainability - Technologies

Technologies	Criteria
Infrastructure	• Availability and number of the city Wi-Fi access points • Share of households with Internet access • Coverage of citizens with the mobile batch communication • Degree of penetration of the fibre-optic network • Number of Wi-Fi hotspots in the private and corporate segments • Tariffs for the broadband Internet connection and mobile Internet as a percentage of GDP • Connection speed of the fixed broadband in the private and corporate segments • Network capacity
Data sources	Open data and electronic payments • Data openness and presence of public authorities in the web • Number of datasets available on the portals of open data • Electronic and mobile payments Citizens • Degree of Internet penetration • Degree of mobile penetration • Proportion of smartphone owners • Proportion of PC and laptop owners • Proportion of broadband Internet subscription in the private sector • Number of visitors of municipal services web-portal The IoT-sensor devices • Road traffic • Public transport • Cycling • Parking • Street lighting • Electricity grids • Buildings • Waste removal and disposal • Water • Air and noise • Density of CCTV cameras
Data-driven decisions and applications	• Transport management • Traffic management • Street lighting management • Mobility management • Waste management • Energy management • Environmental control and monitoring • Buildings management • Urban metabolism analysis • Public safety and healthcare • Citizen participation • Planning and design

Table 4 (b): A summary of the data-driven smart city solutions for sustainability - Competences

Competences	Functions
Horizontal information platforms	• Providing open platforms connecting all the sensors installed in the city and the data obtained from them • Aggregating and standardizing the flows of functional and territorial data from municipal sources, systems of state control (mobility, energy, noise level, pollution level, etc.), business environment, and other state agencies (hospitals, cultural institutions, universities, etc.), as well as from various detectors and cameras for their subsequent integrated analysis and visualization in 3D format • Solving the problems of data disconnection in the city through the open operating system integrating and processing the information generated by the city • Reworking and repackaging the collected data for daily consumption by different stakeholders • Allowing the city authorities and third party users to gain access to the received data in a more structured and convenient manner for software development • Providing comprehensive solutions to complex urban problems by integrating the self-contained and unconnected technological solutions and information systems used in different city functional departments • Improving the efficiency and performance of implemented applied technological solutions • Allowing the city authorities and other users to take decisions on the optimization of the city activities in the long and short-term.
Operations centers and dashboards	• Using visualization sites to help both expert and no-expert users interpret and analyze information, and to allow citizens to monitor the city for themselves and for their own ends • Employing integrated, real-time data to track the performance of the city and to communicate the live feeds of real-time information to citizens in regard to a number of areas • Enabling automated systems to respond to citywide events by making immediate decisions pertaining to various urban areas • Overcoming urban challenges, keeping citizens up-to-date, and developing applications based on the standardized and published open data • Creating innovative platforms, promoting big data use and application, introducing data-driven technologies, and providing expert assistance
Strategic planning and policy office	• Promoting smart approaches through planning systems—making extensive use of data to guide urban planning and design and to encourage developers to deploy digital infrastructure to future proof new developments • Analyzing population displacement and movement data for the strategic planning of city infrastructures, districts, and streets, thereby taking into account the emerging demands from the population • Integrating information on the expectations/uses of the residents of the existing city districts in the construction of scenarios in response to the need for renewal, redevelopment, and development projects • Developing master and comprehensive plans based on the analysis of the city data • Integrating data-driven technology solutions and urban design solutions when developing urban plans and urban development projects • Using a one-stop data analytic hub to bring and weave together data from a variety of city agencies and departments in order to regulate and govern the city and to solve related issues • Collating and analyzing data from a variety of city departments to enable the city authorities to make decisions more effectively in the fight against crime, and provision of public safety and quality of life of the city residents Prioritizing, based on data analysis, the development of the municipal system, and ways to improve the efficiency and effectiveness in the provision of urban services, enforcement of laws, as well as transparency of the city authorities. Among the primary directions of the initiatives to deal with in this regard are: • Support of the city's functions by communication with other city agencies, e.g., adoption of resolutions in the form of models based on data analysis • Data transfer by establishing a platform for exchange of data among various departments, combining data from different sources of various agencies and third party organisations. This can occur through cooperating with the ICT department and the operations centers of the city • Creation of open data portal to be available to anyone interested • Developing and implementing strategies for technological development in the city • Addressing issues of city-wide coordination and cooperation in the field of technologies, playing a bridging role, and advising various city agencies and departments on technological innovation

Training and educational programs and institutes	• Developing educational programs at the intersection of big data analytics, sustainable development, and urban planning and development • Providing specialized academic programs within urban analytics, urban computing, and data-driven urban sustainability • Offering a large number of educational programs with data science and analytics discipline • Introducing data-driven technologies for urban management • Implementing initiatives for developing competencies in a number of data science and analytics areas in relation to urban sustainability by conducting seminars and providing trainings to improve the level of the applied technological knowledge in this regard.
Innovation labs and research centers	• Creating multidisciplinary teams based on practical know how, long–standing experience, international expertise, and access to global networks • Enabling interaction and promoting cooperation between scholars, researchers, industry experts, business professionals, and thought leaders to enhance research opportunities, academic excellence, real-world problem solving, and knowledge creation and dissemination • Providing the ground for developing and testing innovative technological solutions for urban management • Featuring the latest developments in data-driven technologies and solutions and demonstrating how they are applied in real-world settings • Developing urban intelligence functions for improving and optimizing city operations, functions, services. designs, and strategies • Understanding, enhancing, and applying the leading city practices • Integrating resources and expertise for the benefits of the whole city through collective intelligence • Managing, analyzing and visualizing different kinds of projects • Supporting the city authorities in visioning, strategizing, and implementing sustainable development as a set of objectives and targets.

The environmentally data-driven smart sustainable city solutions play a significant role in improving and advancing environmental sustainability in the context of smart cities as well as sustainable cities. Findings indicate that smart grids, smart meters, smart buildings, smart environmental monitoring, and smart urban metabolism are the main data-driven smart solutions applied for improving and advancing environmental sustainability (Bibri & Krogstie, 2020c). There is a clear synergy between these solutions in terms of their interaction or cooperation to produce combined effects greater than the sum of their separate effects—with respect to the environment. This involves energy efficiency improvement, environmental pollution reduction, renewable energy adoption, as well as real-time feedback on energy flows, with high temporal and spatial resolutions. The identified solutions have been incorporated in Table 4.

A Framework for strategic sustainable urban development planning

The integrated framework (Fig. 2) is derived from the aforementioned tables in terms of the core dimensions of compact cities, eco-cities, and data-driven smart cities, and environmentally data-driven smart sustainable cities. The framework attempts to capture in a structured manner the underlying components of the novel model for data-driven smart sustainable cities of the future. Accordingly, there are four basic categories of criteria that are used in defining data-driven smart sustainable cities of the future, namely compact urban strategies, ecological urban strategies, data-driven technologies and solutions for sustainability, and data-oriented competences. The basic idea revolves around the integration of the strategies of sustainable cities with the applied solutions of data-driven smart cities. This is predicated on the assumption that the big data technologies and their novel applications associated with smart cities have great potential to improve and advance the design strategies and technology solutions pertaining to sustainable cities in regard to their contribution to the environmental, economic, and social goals of sustainability.

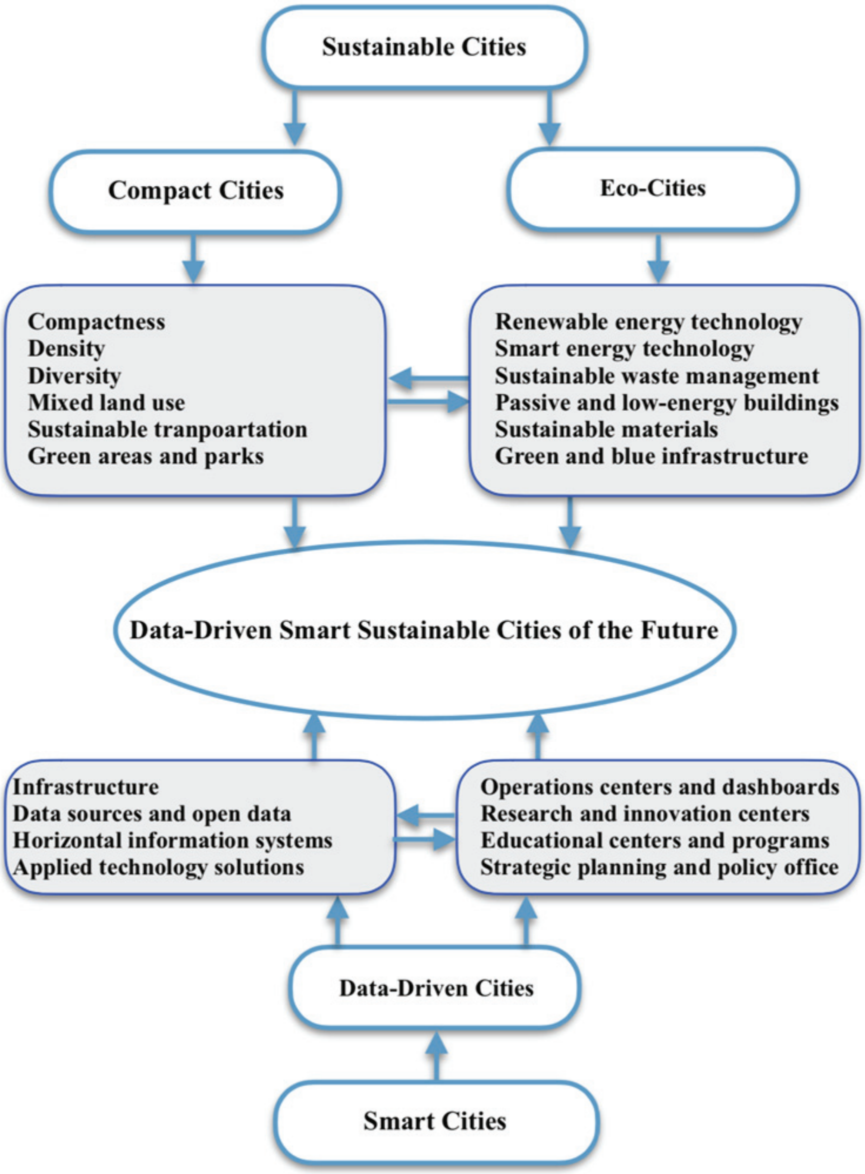

Fig. 2: A framework for strategic sustainable urban development planning

In addition, this integrated framework represents a conceptual structure that is intended to serve as an input to Step 6 in terms of guiding the backward-looking analysis of the backcasting study associated with the development of the strategies and pathways needed to achieve the future vision, namely:

> *A form for human settlements that secures and upholds environmentally sound, economically viable, and socially beneficial development through the synergistic integration of the more established strategies of sustainable cities and the more innovative applied solutions of data-driven smart cities towards achieving the long-term goals of sustainability.*

Conclusion

Big data technologies are certainly enriching our experiences of how cities function. They are offering many new opportunities for enhancing decision-making and generating deep insights with respect to our knowledge of how to monitor, understand, analyze, and plan cities to improve sustainability, efficiency, resilience, equity, and the quality of life. However, whether these developments will be to our collective advantage or disadvantage is yet to be seen for there is undoubtedly a dark side to all technological developments.

This paper set out to identify and integrate the underlying components of a novel model for data-driven smart sustainable cities of the future. We outlined and described the urban and technological dimensions that are necessary for developing the future model of urbanism. These dimensions are distilled based on the four case studies conducted within the frameworks of compact cities, eco-cities, data–driven smart cities, and environmentally data-driven smart sustainable cities. Subsequently, we combined and integrated these models of urbanism in regard to their strategies and solutions into a framework for strategic sustainable urban development planning. This framework leads to the final step of the futures study, which involves developing the strategies and pathways (sub-strategies) necessary for attaining the overall goal of the future vision.

The compact city and eco-city strategies and their integration have recently been enhanced and strengthened through new planning practices, and are increasingly being supported and leveraged by the applied technology solutions offered by the data-driven smart city, especially within those countries that have the highest level of sustainable development practices. The ultimate aim is to develop and implement more effective approaches to the balanced integration of the three dimensions of sustainability, and to produce combined effects of the strategies and solutions pertaining to the prevailing and emerging paradigms of urbanism that are greater than the sum of their separate effects with respect to the tripartite value of sustainability.

The field of sustainable urbanism needs to extend its boundaries and broaden its horizons beyond the ambit of the built form, ecological design, and green technology characterizing sustainable cities to include technological innovation opportunities by unlocking and exploiting the potential of advanced ICT. Worth pointing out is that sustainable cities epitomize complex systems par excellence, more than the sum of their parts and developed through a multitude of individual and collective decisions from the bottom up to the top down. As such, they are full of contestations, conflicts, and contingencies that are not easily captured, steered, and predicted respectively. Therefore, sustainable cities are increasingly embracing what advanced ICT has to offer to respond to the complexities they inherently embody so as to improve their performance outcomes. Indeed, computational and scientific approaches are very important for understanding and dealing with urban complexities (e.g., Batty Axhausen, Giannotti, Pozdnoukhov, Bazzani, Wachowicz, Ouzounis, & Portugali, 2012; Bibri, 2018a, 2018c, 2019a, 2019d, 2019e, 2020a; Bettencourt, 2014). And together with political/social solutions, citizen participation, and deliberative democracy, they should play a pivotal role in solving some of the special conundrums and wicked problems of sustainable cities.

It must be noted that there currently are neither real examples of a truly data-driven smart sustainable city that have actually been delivered to the world, nor a future proofing of the IoT and big data technologies to ensure that they can be adapted, modified, and built upon in a more effective way over the next 25 years or so in response to the dynamic changes of technology and fast-moving hi-tech industry. Therefore, the planned data-driven solutions must be evaluated through an actual implementation and its expected positive outcomes in order to determine the actual opportunity for improving and advancing sustainability. The road ahead promises to be exciting as more cities become aware of the great potential and clear prospect of integrating the sustainable city and the smart city as landscapes and approaches—for meaningful uses and collective advantages.

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Paper 11

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TECHNICAL ARTICLE

A Novel Model for Data-Driven Smart Sustainable Cities of the Future: A Strategic Roadmap to Transformational Change in the Era of Big Data

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The conscious push for sustainable cities to be smarter and thus more sustainable in the era of big data is due to the problematicity surrounding their development planning approaches and operational management mechanisms, as well as the fragmentation of their designs and technologies. This has a clear bearing on their performance with respect to the contribution to and balancing of the goals of sustainability. This situation is compounded by the negative consequences of the expansion of urbanization, an irreversible global trend involving a multitude of environmental, social, economic, and spatial conditions that pose unprecedented challenges to policymakers and planners. The underlying argument is that more innovative solutions and sophisticated methods are needed to enable sustainable cities to tackle the kind of problems and complexities they embody. This in turn brings us to the question related to the weak connection between sustainable cities and smart cities as approaches as well as their extreme fragmentation as landscapes, both at the technical and policy levels. Therefore, sustainable cities need to embrace and leverage what smart cities have to offer so that they can optimize, enhance, and maintain their performance and thus achieve the desired outcomes of sustainability. This paper aims to develop a novel model for data-driven smart sustainable cities of the future, and in doing so, it provides a strategic planning process of transformative change towards sustainability. This model combines and integrates the prevailing paradigms of sustainable urbanism and the emerging paradigms of smart urbanism —based on the outcomes of the four case studies conducted on compact cities, eco-cities, data–driven smart cities, and environmentally data-driven smart sustainable cities. As the core of this aggregate model is how to bring about the different forms of infrastructural transformations needed to reach a vision of a sustainable future in the era of big data. Especially, it has become feasible to attain important improvements and advancements of sustainability by amalgamating sustainable cities and smart cities thanks to the proven role of advanced ICT and the untapped potential of data-driven technologies.

Keywords: Data-driven smart sustainable cities; sustainable cities; smart cities; compact cities; eco-cities; infrastructure; strategic planning; sustainability; data-driven technologies

1. Introduction

Cities are a mark of human civilisation and play a central role in the pursuit of new paradigms of thinking to bring about major transformations to the way people live. Sustainability has, over the last four decades, been one of the most influential paradigms of thinking within urbanism. Modern cities holding unparalleled potential to address and overcome the challenges of sustainable development largely depends on how they can be planned, designed, and managed in response to global trends, scientific discoveries, and technological advances. This is clearly reflected in the Sustainable Development Goal (SGD 11) of the United Nations' 2030 Agenda—Sustainable Cities and Communities (UN 2015a). Appropriately redesigning and restructuring urban places as sustainable cities and adopting innovative solutions to make urban living more sustainable is a continuous endeavor towards achieving the long-term of goals sustainability.

Compact cities and eco-cities are the central paradigms of sustainable urbanism and the most prevalent and advocated models of sustainable cities. Numerous recent national and international policy reports and papers state that these two models contribute, though to varying degrees, to resource efficiency and reliability, environmental protection, socio-economic development, social cohesion and inclusion, quality of life and well-being, and cultural enhancement (Bibri 2020a). It is argued that the compact city model is able to contribute to and support the balancing of the three goals of sustainability (e.g., Bibri, Krogstie and Kärrholm 2020; Burton 2002; Jenks and Dempsey 2005; Hofstad 2012; Jenks and Jones 2010; OCED 2012), and that the eco–city model is able to achieve the goals of environmental

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sustainability and to produce some economic and social benefits of sustainability (Bibri and Krogstie 2020a; Joss 2010; Joss, Cowley and Tomozeiu 2013; Kenworthy 2006; Mostafavi and Doherty 2010; Pandis and Brandt 2011; Rapoport and Vernay 2011; Suzuki et al. 2010).

Transformative processes within sustainable cities have been in focus for some time now. The motivation for achieving the United Nations' SGD 11 has increased the need to understand, plan, and manage sustainable cities in new and innovative ways (UN 2015a). In this respect, the United Nations's 2030 Agenda regards advanced ICT as a means to promote socio–economic development and protect the environment, increase resource efficiency, achieve human progress and knowledge in societies, upgrade legacy infrastructure, and retrofit industries based on sustainable design principles (UN 2015b). This relates to the multifaceted potential of smart cities, which has been under study with respect to the role of big data technologies and their novel applications in strategic sustainable development within the framework of 2030 Agenda (UN 2015c). The abundance of urban data, coupled with their analytical power, opens up for new opportunities for innovation in sustainable cities. This in turn means tackling the problems and challenges facing sustainable cities in their endeavor to make actual progress towards achieving the vision of sustainability.

Big data technologies are heralding a new era wherein sustainable cities are morphing in response to what has been identified as data-driven urbanism. This transformation—which entails how sustainable cities are being monitored, understood, analyzed, and thus organised, planned, controlled, and regulated—is manifest in the increasingly level of the development and implementation of data-driven technology solutions in their management mechanisms and development planning approaches. In fact, big data technologies have, in the context of sustainability, become as essential to the functioning of smart cities (e.g., Angelidou et al. 2017; Bibri 2019a; Bibri and Krogstie 2020b, c; Bettencourt 2014; Eden Strategy Institute 2018; Hashem et al. 2016; Kumar and Prakash 2016; Nikitin et al. 2016; Perera et al. 2017) as to that of sustainable cities (e.g., Bibri 2018, 2020b, c; Bibri and Krogstie 2017a, b, 2020a, c; Pasichnyi et al. 2019; Shahrokni et al. 2014; Shahrokni, Levihn and Brandt 2014; Shahrokni et al. 2015; Shahrokni, Lazarevic and Brandt 2015; Sun and Du 2017; Thornbush and Golubchikov 2019).

The conscious push for sustainable cities to be smarter and thus more sustainable in the era of big data is due to the problematicity surrounding their development planning approaches and operational management mechanisms, as well as the fragmentation of their designs and technologies. This has a clear bearing on their performance with respect to the contribution to and balancing of the goals of sustainability. Over the last two decades, research within the field of sustainable urban forms, especially compact cities and eco-cities, has produced conflicting, uncertain, and non-conclusive results (e.g., Bibri 2020b, c; Bibri and Krogstie 2017a; Cugurullo 2016; Jenks and Dempsey 2005; Kaido 2005; Kärrholm 2011; Lim and Kain 2016; Neuman 2005; Williams 2010) concerning the actual benefits they claim to deliver. This is compounded by the unprecedented issues engendered by the escalating urbanization and their implications for jeopardizing sustainability. Today, urbanization is one of the greatest environmental, economic, and social challenges that sustainable cities are facing. In recent decades, urban growth has been dramatic, a climate which has made it more challenging for sustainable cities to reconfigure themselves more sustainably without the use of advanced ICT. In a nutshell, new circumstances require new responses. Bibri and Krogstie (2019a) provides a comprehensive review of sustainable urban forms (eco–cities and compact cities), highlighting their inadequacies, shortcomings, struggles, and bottlenecks, as well as the role and potential of advanced ICT in addressing these issues and problems. Most of which tend to relate to how sustainable cities have long been studied, understood, and planned. This pertains to data scarcity, inherent limitations of traditional research methods, inefficient management processes, and long-term planning approaches. This is dramatically changing thanks to the multifaceted potential of smart cities as enabled predominately by the IoT and big data technologies. As a result, many opportunities are yet to explore as to integrating sustainable cities and smart cities in terms of their operational management and development planning on the basis of advanced computational data analytics, thereby mitigating their extreme fragmentation and weak connection (e.g., Ahvenniemi et al. 2017; Angelidou et al. 2017; Bibri 2019b, 2020b, c; Bifulco et al. 2016; Kramers, Wangel and Höjer 2016) under what is labelled "data–driven smart sustainable cities."

This paper aims to develop a novel model for data-driven smart sustainable cities of the future, and in doing so, it provides a strategic planning process of transformative change towards sustainability. This model combines and integrates the prevailing paradigms of sustainable urbanism and the emerging paradigms of smart urbanism — based on the outcomes of the four case studies conducted on: (1) compact cities (Bibri, Krogstie and Kärrholm 2020), (2) eco-cities (Bibri and Krogstie 2020a), (3) data–driven smart cities (Bibri and Krogstie 2020b), and (4) environmentally data-driven smart sustainable cities (Bibri and Krogstie 2020c). The case study research is associated with the empirical phase of a futures study that consists of 6 steps, each with several guiding questions to answer. This paper reports the outcome of Step 6, which involves answering the following five guiding questions:

1. What built infrastructure changes are necessary for reaching the vision of the desired future?
2. What sustainable urban infrastructure changes are necessary?
3. What smart urban infrastructure changes are necessary?
4. What social infrastructure changes are necessary?
5. What technological infrastructure changes are necessary?

Important to note is that the framing of this paper as a set of planning actions and policy measures is justified by the fact that it is concerned with the decisive steps and strategic pathways that should be taken to attain the vision of the desirable future. The primary intent is to provide recommendations for government officials, policymakers, planners, designers, developers, industry experts, and other stakeholders on how to build a data-driven smart sustainable city of the future.

This paper is organised into four sections: Section 2 briefly introduces the methodological framework for the futures study. Section 3 presents the results, detailing the strategic planning process of backcasting in terms of its objectives, targets, vision, and strategies and pathways. Section 4 discusses the results. This paper ends, in Section 5, with some concluding remarks.

2. Research Methodology

The methodological framework applied in the futures study combines and integrates normative backcasting and descriptive case study as qualitative approaches. The backcasting approach was employed to achieve the overall aim of the futures study. The case study approach, which is associated with the empirical phase of the futures study, was adopted to examine and compare two of a total of six cases from the ecologically and technologically leading cities in Europe within each of the frameworks of compact cities, eco-cities, data–driven smart cities, and environmentally data-driven smart sustainable cities. Bibri (2020d) dedicates a whole article to the methodological framework for strategic data-driven smart sustainable city planning whose core objective is clarifying which city model is desired and working towards that specified outcome. **Table 1** presents the guiding questions for each of the six steps in the futures study, and highlights the five questions addressed by this paper in bold.

Table 1: The guiding questions for each step in the backcasting-oriented futures study.

The guiding questions for the backcasting-oriented futures study	Methods and tools
Step 1: Detail strategic problem orientation (Part 1) 1. What is the model of urbanism to be studied? 2. What are the aim, purpose, and objectives of the backcasting study in relation to this model? 3. What are the long–term targets declared by the goal–oriented backcasting approach? 4. What are the objectives these targets are translated to for backcasting analysis?	Research design and problem formulation
Step 2: Detail strategic problem orientation (Part 2) 1. What are the main prevailing trends and expected developments related to the model to be studied? 2. What are the key sustainability problems associated with the current model of urbanism and what are the causes? 3. How is the problem defined?	Trend analysis and problem analysis
Step 3: Generate a sustainable future vision 1. What are the demands for the future vision? 2. How does the future model of urbanism look like? 3. How is the future model of urbanism different from the current model of urbanism? 4. What is the rationale for developing the future model of urbanism? 5. Which sustainability problems have been solved and which technologies have been used in the future vision?	Creativity method
Step 4: Conduct empirical research 1. What is the justification for the methodological framework to be adopted? 2. Which category of case study design is most relevant to investigating the dimensions of the future model of urbanism? 3. How many case studies are to be carried out and what kind of urban phenomena should they illuminate? 4. To what extent can this investigation generate new ideas and illustrate the theories applied and their effects, as well as underpin and increase the feasibility of the future vision?	Case study method
Step 5: Specify and Integrate the components of the future model of urbanism 1. What urban and technological components are necessary for the future model of urbanism? 2. How can all these components be integrated into a framework for strategic sustainable urban development planning? 3. What are the key benefits, potentials, and opportunities of the future model of urbanism?	Creativity method
Step 6: Perform backwards–looking analysis 1. What built infrastructure changes are necessary for attaining the future vision? 2. What sustainable urban infrastructure changes are necessary? 3. What smart urban infrastructure changes are necessary? 4. What social infrastructure changes are necessary? 5. What technological infrastructure changes are necessary? 6. What institutional changes are necessary?	Backcasting analysis

Source: Bibri (2020d).

2.1. Backcasting as a Strategic Planning Process

The term "backcasting," which was coined by Robinson in 1982, can denote a concept, a study, an approach, a methodology, a framework, or an interactive process among stakeholders. Hence, it has been defined in multiple ways. Robinson (1990, p. 823) defines backcasting as a normative approach which works "backwards from a particular desired end point to the present in order to determine the feasibility of that future and what policy measures would be required to reach that point." Thus, backcasting is a planning process by which a desired outcome is envisioned and articulated, followed by the question: "what do we need to do today to reach that specified outcome?" (**Figure 1**) This question is about figuring out the "next steps," which are quite literally the next concrete actions to undertake.

In recent years, backcasting has been mostly applied in the futures studies that deal with long-term problems and sustainability solutions (see, e.g., Åkerman 2005; Akerman and Höjer 2006; Höjer, Gullberg and Pettersson 2011; Miola 2011; Quist et al. 2011; Quist 2007; Vergragt and Quist 2011; Wangel 2011). The backcasting process in the futures study represents a strategic planning tool for facilitating the progress towards achieving the goals of sustainability for those cities that are badging or regenerating themselves as sustainable, or manifestly planning to be or become smart sustainable in the era of big data.

2.2. Descriptive Case Study

The descriptive case study approach was applied in the four case studies to investigate the prevailing models of sustainable urbanism and the emerging models of smart urbanism (Step 4). The intention of this investigation is to identify the underlying components of the new model of urbanism in terms of its core dimensions, strategies, and solutions, and then to integrate these components into an applied framework for strategic sustainable urban development planning (Step 5). This is in turn intended to guide the strategic planning process of transformative change towards sustainability, which represents the novel model for data-driven smart sustainable cities of the future (Step 6). Overall, by carefully studying any unit of a certain universe, we find out about some general aspects of it, at least a perspective that guides subsequent research. Case studies often represent the first scholarly toe in the water in new research areas.

The case study is a descriptive qualitative methodology that is used as a tool to study specific characteristics of a complex phenomenon. The descriptive case study approach, as defined by Yin (2009, 2014, 2017), was identified as the most suitable methodology for the empirical phase of the futures study. This methodology has been chosen considering the nature of the problem being investigated, the research aim, and the present state of knowledge with respect to the topic of data-driven smart sustainable cities. In this context, it involves the description, analysis, and interpretation of the four urban phenomena, with a particular focus on the prevailing conditions pertaining to plans, projects, and achievements. That is, how the selected cities behave as to what has been realized and the ongoing implementation of plans based on the corresponding practices and strategies for sustainable development and technological development. Accordingly, the four case studies examine contemporary real-world phenomena and seek to inform the theory and practice of data-driven smart sustainable urbanism by illustrating what has worked well, what needs to be improved, and how this can be done in the future. They are particularly useful for understanding how different elements fit together and (co-)produce the observed impacts in a particular urban context based on a set of intertwined factors.

3. The Results: The Strategic Planning Process of Backcasting

As a roadmap to transformational change, the backcasting process articulates strategic thinking—the why—behind both the vision of the future and the plan for getting

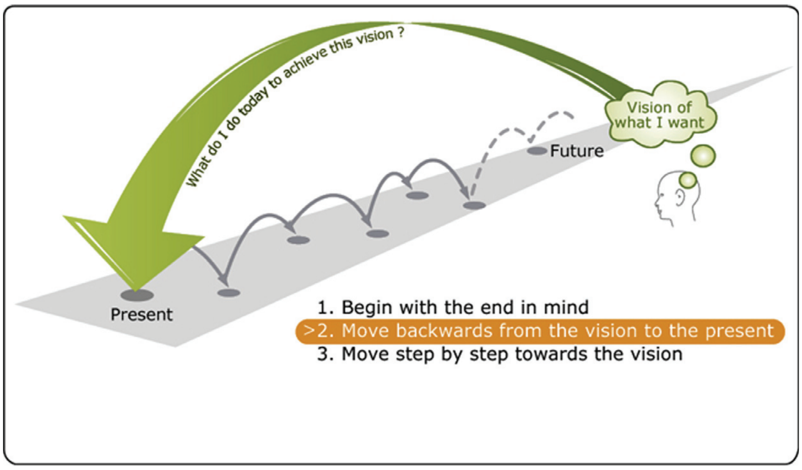

Figure 1: The backcasting process from the Natural Step.
Source: Holmberg (1998).

there. Strategic planning denotes a systematic process of generating a vision of a desirable future and translating it into broadly defined objectives and targets, and then identifying a sequence of actions and measures to achieve that specified future. Accordingly, this section is structured into three main phases, (1) the vision of the future, (2) the objectives and targets of sustainable development, and (3) the strategies and pathways for transformative change.

3.1. The Future Vision

The vision of the future is where the problems, issues, and challenges related to sustainable cities (Bibri and Krogstie 2019a) have been solved by means of the data-driven technologies and solutions offered by smart cities of the future. However, the overall goal, which builds the vision of what the future should look like once manifested, is the indicator established to determine whether the objectives have successfully been achieved. The data-driven smart sustainable city is envisioned as (Bibri and Krogstie 2020d, p. 89):

> "*A form of human settlements that secures and upholds environmentally sound, economically viable, and socially beneficial development through the synergistic integration of the more established strategies of sustainable cities and the more innovative solutions of data-driven smart cities towards achieving the long-term goals of sustainability*."

In constructing the future vision, we have attempted to retain the best of what we already have that have been successfully enacted in real-world cities, making use of the things that have been demonstrably better in the past, while being selective in adopting the best of what is emerging and promising, making use of the things that will add a whole new dimension to sustainability in terms of harnessing its synergic effects, balancing its dimensions, and thus boosting its benefits.

3.2. The Objectives and Targets

The future vision is translated into broadly defined objectives and targets, which are of a long-term nature. The objectives and targets can also be used to develop the future vision. The targets are established first as specific desired outcomes that support the achievement of the objectives. These define an endpoint of concern and the direction of change that is preferred. The targets and objectives are to be—specific, measurable, achievable, relevant, and targeted when adopting the future model of urbanism. They are decided on according to what the data-driven smart sustainable city of the future aspires to achieve, an ambition which can be adapted to existing sustainable cities in their own contexts.

The objectives describe the measurable contribution of the data-driven smart sustainable city of the future as to achieving the overall goal of the future vision. Therefore, they define what is to be achieved and should have a specified timescale and be linked to the performance of the data-driven smart sustainable city of the future to ensure that policy commitments are prioritized and addressed in terms of improving and advancing the environmental, economic, and social goals of sustainability. This improvement should also be continual in line with sustainability policies in relevance to the national and local context of existing sustainable cities so that new objectives can be agreed on when the original objectives have been met. However, the objectives are of a qualitatively descriptive nature because the future vision is not concerned with a given sustainable city, or departs from a basic standard in mind accordingly. With that in regard, the data-driven smart sustainable city of the future aims to achieve the objectives of sustainable development, the most prominent among them are presented in **Table 2**.

The targets are the indicators that are established to determine how successfully the objectives have been achieved by providing relevant benchmarks for the compact, ecological, and technological components of the data-driven smart sustainable city of the future. This involves how synergistically these components are integrated, cooperate, and beneficially complement one another. The targets can quantify or qualify the objectives over time. The specific targets set in relation to the future vision are specified in terms of the dimensions, strategies, and solutions of the four investigated models of urbanism. They help to set up a clear course of action and guide the future vision. The target-setting here denotes the strategic process to establish performance goals for the physical, environmental, economic, social, and technological areas of the data-driven smart sustainable city of the future. Each area uses a different tool that starts with establishing a baseline, e.g., how much energy is currently being used, or how dense and diverse is a given urban area or district. In the context of the futures study, the targets are of a qualitatively descriptive nature because the future vision is not concerned with a given sustainable city, or departs from a basic standard in mind accordingly. Nonetheless, the qualitative targets should, when planning the development of the data-driven smart sustainable city of the future, be turned into quantifiable targets that can be achievable within an agreed timescale in accordance with the objectives. This in turn depends on the nature of the areas targeted (e.g., GHG emissions reduction, energy efficiency, well-being, etc.), the level of progress already made in these areas, and so forth. As to the level of progress, for example, the targets should be set in the areas where improvement is most needed or prioritized in order to meet the requirements for regulatory compliance, to improve performance, to reduce risks, and so on.

Table 2: The prominent objectives of sustainable development.

- Reduced energy consumption and carbon footprint
- Improved resource efficiency with minimal environmental impacts
- Minimized waste
- Increased use of sustainable materials
- Reduced air and noise pollution
- Reduced automobile use
- Preservation of open space and sensitive ecosystems
- Improved social justice and equity
- Enhanced quality of life and well-being
- Liveable and community-oriented human environments

The future vision as a long-term goal represents the set of targets that should move the city from its current state (sustainable) to its future state (data-driven smart sustainable). Hence, these targets incorporate the objectives of sustainable development as well as the objectives of technology associated with the readiness of the city to introduce data-driven technology in, and the implementation of applied technology solutions for, city operational management and development planning with regard to sustainability. Accordingly, they should be based on the synergistic integration of the strategies and solutions of the four investigated models of urbanism (see **Table 3**).

Furthermore, one objective may involve the different categories of the targets, e.g., reducing energy usage includes targets related to building density, green energy, smart energy, passive and net-zero energy building, sustainable transport, smart transport, and so forth. Each of these targets may in turn include a set of sub-targets. Generally, a strategic vision can have multiple goals and each goal can have many objectives. At the same time, each objective can be linked to multiple targets and each target can be linked to various key performance indicators (KPIs). The targets specified represent the key areas that drive urban sustainability performance and the way it can be improved and advanced with the support of data-driven smart technologies and solutions. Finding a way to measure these areas is normally followed by, as a natural next step, starting setting performance targets.

The data-driven smart sustainable city of the future should establish CityScore as an online dashboard to show how the city government is performing against its targets in the areas identified on a wide range of metrics. The metrics measured can be used as a gauge of how well the city government is serving its citizens and responding to their concerns in regard to the three dimensions of sustainability. The daily activity updates make performance and progress transparent to the public and city administrators. A single, combined number can summarize how the administration is performing overall. Tracking performance against targets enables problem areas to be quickly identified and remedied, and offers citizens the opportunity to hold administrators to account. Aggregating and dividing the data collected automatically by sensors as well as by city workers using their mobile devices by the target figure can generate a daily, weekly, or quarterly score: above 1 means the city is exceeding its targets, below 1 means it is falling short.

The targets should be clear and there should be no ambiguity about the objectives that should be prioritized. This ensures that stakeholders understand how the different objectives are being attained and balanced. This in turn can help secure stakeholders' buy-in and support. In particular, the ICT infrastructure should be planned, implemented, and managed while being dependent on the initiative by and interest of the other stakeholders involved in the sustainability efforts, including planners, developers, architects, building owners, utilities, energy cooperatives, and citizens. The initiatives of these stakeholders should be coordinated in order for them to be able to work together more effectively and support each other. Among the benefits of setting the targets in this context are:

- Establishing clear goals for various stakeholders and purposes (e.g., organisations, institutions, projects, investments, etc.)
- Motivating people (planners, developers, industry experts, citizens, etc.) by clarifying their expected performance and how they can measure progress
- Providing a benchmark against which improvements can be measured
- Demonstrating commitment to the agenda and policies of sustainable development

Worth noting is that the above stated targets embody the targets of the SDG 11 (**Table 4**). These are slightly adapted from the United Nations (2015a) as the focus of the futures study is on the cities that are already badging or regenerating themselves as sustainable, or manifestly planning to be or become smart sustainable.

Table 3: The core compact, ecological, and technological targets of the future model of urbanism.

- Increased compactness of urban space
- High density and diversity of buildings
- Multidimensional mixed uses: social mix, physical land use mix, economic mix, and temporal mix
- Prioritized sustainable transportation and its integration with smart transportation
- Multifunctional green infrastructure for ecosystem services and biodiversity
- Balanced mixture of low-energy, energy-efficient, and passive buildings
- Large–scale net–zero and locally produced solar energy houses
- Sustainable energy system and its integration with smart energy system
- Sustainable waste system and its integration with smart waste system
- High degree of the readiness of the city to the integration of advanced technology in its management:
  - High availability and development level of the infrastructure and big data analytics competencies required for the functioning of the city
  - New and extensive sources of data and a high level of support for open and standard data
- High degree of the implementation of applied technology solutions for the city management:
  - High level of the development of applied data-driven solutions for the city operational management and development planning related to the various areas of sustainability
  - Established data-oriented competences pertaining to research, innovation, strategic planning and policy, education, and professional training.

Table 4: The SDG 11 targets embodied in the future vision.

1. Ensure access for all to adequate, safe, and affordable housing and basic services.
2. Provide access to safe, affordable, accessible, and sustainable transport systems for all.
3. Enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management.
4. Strengthen efforts to protect and safeguard the natural and cultural heritage.
5. Reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.
6. Provide access to safe, inclusive and accessible, green and public spaces.
7. Substantially increase the number of human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation of and adaptation to climate change, and resilience to disasters.

Source: Adapted from United Nations (2015a).

3.3. The Strategies and Pathways for Transformative Change

This phase entails building a feasible and logical path between the state of the future and the present based on the criteria defined for the future vision. Such path represents a set of strategies and pathways to be pursued in order to bring about the needed transformative change towards sustainability. Determining the strategies and the specific pathways to execute them is the main part of the effort to achieve the overall goal of the future vision by meeting the specified objectives and targets. At the heart of these strategies and pathways is the practice-oriented process of designing and developing the data-driven smart sustainable city of the future. Different multiple strategies are needed in order to attain the future vision. To employ each of these strategies in turn requires a set of specific actions, sequences of actions, and agendas within each strategy, ways of achieving specified results. However, as cities generally need to be able to respond to new global trends and shifts, it is important for the future vision, strategies, and pathways to have flexibility as well as some firmness. The future vision needs to remain firm and should be the anchor that holds all the rest together. The strategies as a form of long-term plan may need to pivot in response to external factors such as global trends and technological shifts. The pathways are the most flexible in terms of adjustment and modification, especially the future vision does not pertain to a given sustainable city. In a nutshell, the goal needs to be developed and planned strategically, held to be achieved, and the pathways that can help move towards fulfilling the strategies need to be flexible. The key strategies and pathways are presented next in accordance with the five dimensions of the landscape of the data-driven smart sustainable city of the future, namely:

1. Built infrastructure
2. Sustainable urban infrastructure
3. Smart urban infrastructure
4. Social infrastructure
5. Technological infrastructure

3.3.1. Built Infrastructure

The built infrastructure involves the patterns of the physical objects in the city pertaining to the built-up areas as well as those areas planned for new development and redevelopment together with transport, communication, anergy, and waste systems. The compact and ecological dimensions of urban design characterize most of the built infrastructure as regards its buildings, blocks, streets, open space, public space, green space, and essential urban infrastructure.

3.3.1.1. Compact Design of Urban Form

Urban form denotes the physical aspects that characterize the built-up areas. The form of the city is seen as a salient factor for enacting more sustainable, efficient, equitable, and livable urban environments though design. It is associated with the development strategies related to urbanization dimensions, namely physical (land use change), geographical (population), economic (agglomeration), and societal (social and cultural change). These largely pertain to the design strategies of the compact city, namely compactness, density, multidimensional mixed-land use, sustainable transformation, and green open space.

The strategies for development planning are based on a number of important challenges, notably increasing population, plans to create more jobs, new demands from the business sector, the possibility of a simpler daily life for more people, measures to decrease social inequality and socio-spatial segregation, the development of urban areas for a more closely connected city, plans to enhance transport infrastructure, and the even distribution of green areas and parks. These are at the core of the compactness of the built form.

Main Directions for Compactness

To attain the compactness of the built form of the data-driven smart sustainable city of the future with the expected benefits of sustainability, there are four main directions to take:

- Develop central points:
  - Densify and supplement with more housing and businesses around the central points to make use of the particularly good conditions for a more local city life based on the idea of enabling people to manage day-do-day life by walking, cycling, and public transport.
  - Gather shops and services so that the central points function as local magnets.

  - Make good use of the situation at the central points, with densification in mind.
  - Use the land in a carefully thought-out and efficient manner so that the places take on more city character.
- Make use of what already exists:
  - Use existing resources and investments already made as efficiently as possible.
  - Reinforce, supplement, and further develop in the closely connected building structure already in place.
  - Use the existing infrastructure more efficiently to reduce the effects of traffic on the environment.
  - Counteract traffic congestion.
  - Coordinate the locations of new houses, workplaces, and services with extensions and reinforcements in public transport.
  - Retain and reinforce closely connected public walk-ways between the areas, functions, and buildings.
- Make the biggest effort and muster strength where it makes a difference at most:
  - Prioritize between development areas.
  - Promote brownfield development.
  - Develop new areas on the basis of a holistic approach and overall way of thinking, instead of smaller or scattered supplementary projects.
  - Create variety through more functions in each district, quarter, and building.
  - Cooperate on a broad scale with other stakeholders.
  - Involve different stakeholders in planning measures over a longer period of time to ensure an overall perspective.
- Regulate compact urban development:
  - Increase the effectiveness of regulatory tools.
  - Set minimum density requirements for new development.
  - Establish mechanisms to reconcile conflicts of interests.
  - Strengthen urban rural linkages.
  - Harmonize business policies with compact city policies.

Staged Expansion and Intensification of Urban Fabrics

To pursue these directions, it is important to stage an expansion of the city based on the current level of its compactness with respect to the extent to which land areas can be used close to existing development, or urban development can take place adjacent to existing urban fabrics and structures. This relates to the intensification strategy of compaction, which encompasses a range of substrategies for urban renewal, infill, development, and redevelopment. These substrategies in the context of the data-driven smart sustainable city of the future are to be applied on the six specific urban fabrics that were identified based on the case studies conducted on compact cities and eco-cities (Bibri, Krogstie and Kärrholm 2020; Bibri and Krogstie 2020a). An urban fabric denotes the physical characteristics of urban areas in terms of components, materials, buildings, spatial patterns, scales, streetscapes, infrastructure, networks, and functions, as well as socio-cultural, ecological, economic and organisational structures. The identified urban fabrics together with the applied substrategies of the intensification strategy are presented below:

Build and Develop Centrally

The Central Renewal Area

- Build mixed developments.
- Create attractive meeting places and new parks.
- Prioritize public transport, walking, and cycling.
- Create robust and interconnected urban structure by improving connections.
- Enhance the cultural environment.

The Inner City

- Strive for a living center with attractive and safe city spaces.
- Develop a mix of densely built dwellings, workplaces, shops, businesses, facilities, and public services together with well elaborated public spaces for a pleasant and comfortable everyday life.
- Increase the number of homes.
- Prioritize public transport, walking, and cycling.
- Protect cultural heritage and be respectful in new development.
- Improve green areas and parks.

Concentrate on Strategic Nodes

- Analyze the potential for greater density, which should be based on the existing housing forecast in order to be able to plan for a long-term development of the city.
- Develop brownfield sites first.
- Create and complement with a mix of functions combined with varied public.
- Build with higher densities around interchanges (with good accessibility) and public transport corridors.
- Prioritize density close to the central points of strategic nodes.
- Encourage high quality design to lower perceived density.
- Create good opportunities for walking and cycling.
- Improve transport infrastructure and services and increase accessibility.
- Implement multi-model travelling to support the density and mixed land use of the central points of strategic nodes
- Make use of valuable green areas and corridors.
- Recognize that the green areas are important for the preservation of nature's own integrity, and a significant recreational factor for inhabitants.

Complement and Mix

- Complement the areas that have good access to public transport and are easy to reach by walking and cycling by additional homes, workplaces, and commercial functions, thereby greater variety and a more vibrant city.

- Ensure a mix of housing types and forms as well as of functions.
- Increase diversity and vitality through new development and re-development.
- Improve the match between residents and local services and jobs.
- Encourage the greening of built-up areas.

Reserve Outer Areas for Future Consideration

The outer area, which is not yet developed or about to be developed, should be strategically planned based on the core strategies of the compact city in terms of density, diversity, mixed land use, sustainable transportation, green space, and other design features pertaining to the eco-city with respect to various types of sustainable buildings.

- Unlock the potential for the development of new homes and workplaces in the areas located on the outer edges of the city.
- Provide the opportunity for new development in the long term.
- Invest in urban infrastructure and services prior to new development, especially transport.
- Ensure the feasibility of high quality public transport in order to achieve a certain level of density.
- Have regard to valuable natural, cultural, and recreational heritage.
- Consider developing passive, low-energy, net zero energy, energy efficient, and green buildings.

Build New Districts

Building new districts should be based on the integration of the core strategies of the compact city and the eco-city as planning systems as regards designs and buildings, with support of new technologies.

- Create great diversity of the scales and designs of building densities.
- Make larger and medium scale buildings more frequent as to the distribution of building footprints.
- Create great variety of buildings and building techniques, notably passive solar, low energy, net-zero, energy efficient, and green buildings.
- Use sustainable materials in building construction.
- Use recycled material with the potential of future reuse and long life span in the underlying layers of the streets, alleys, and public spaces.
- Develop multidimensional mixed land use: physical land use mix, economic mix, and social mix.
- Encourage focused investment in public space and foster a sense of place.
- Support various types of housing tenures: the conditions under which buildings or dwellings are held or occupied, with a planning approach focused greatly on safety and equality aspects via the design of different meeting places.
- Develop and implement measures to stimulate the development of affordable housing for all income groups, not too high to serve low and moderate income residents through inclusionary zoning.
- Create a diversity of job–housing balances, household sizes, household structures, cultural diversity, and age groups.
- Invest in and continuously work on reducing socioeconomic disparity and social segregation within the new city districts to unlock its full potential and the city's population and cultural structure.
- Create robust and interconnected urban structure by developing good connections: physical links within and between the different parts of the new city districts, as well as their connection with the existing city districts.
- Forge the physical links between communities within the different parts of the new city districts.
- Remove physical barriers isolating certain areas by improving public transportation infrastructure and services.
- Prioritize public transport, walking, and cycling.
- Make use of valuable green areas Recognize that the green areas are important for the preservation of nature's own integrity, and a significant recreational factor for inhabitants.
- Protect national parks with regard to their specific and sensitive flora and fauna and their cultural heritage
- Create new and evenly distribute parks across the new city districts.
- Develop relevant structures for collaboration between these stakeholders within the city departments.
- Involve local communities in planning and decision–making processes in ways that enable the residents to have a say in the development of the new city districts by inviting them to attend a series of planning workshops, e.g., exploration of strategic options, community planning sessions, and capacity building.
- Collect and analyze data on the movement of residents to plan the new city districts.

3.3.1.2. Ecological Design of Urban Form

Ecological design is a design form which integrates itself with living processes to minimize environmentally negative or destructive impacts. It is associated with the green structure in the city and how it should be developed, distributed, and managed (e.g., Austin 2013; Bibri and Krgostie 2020a; Beatley 2010; Beatley 2000; Farr 2008; Mostafavi and Doherty 2010). The green and blue structure strategy can be broken into eleven substrategies, namely:

1. Greening
2. Rainwater harvesting
3. Ecological diversity
4. Biodiversity
5. Green parks
6. Green streets and alleys
7. Green factor and green points
8. Green roofs
9. Rain gardens
10. Bioswales
11. Permeable Pavements

The green structure strategy relates to the idea of letting nature do the work by designing multifunctional green structure to provide important ecosystem services of various categories, including provisioning, regulating, cultural, and supporting services. To let nature do the work entails ensuring that greenery and water are used as active components in the design and operation of the city. The green structure replaces and complements technical systems, creates a richer plant and animal life, and contribute to human health and well-being. Important to note is that the green structure strategy as an integrated approach is best to be implemented in new urban areas or outer areas with development potential. Also, a number of the aforementioned substrategies can be implemented as part of the individual urban development projects related to the other urban fabrics mentioned earlier, when it is feasible from a design perspective. However, below are the key pathways needed for executing the green structure strategy:

- Ensure the use of greenery and water as active components in the design and operation of the city districts.
- Provide incentives to the residents in the existing city districts to install their own rainwater harvesting systems.
- Design the drainage system in the new city districts to be aesthetically pleasant, with waterfalls, canals, ponds, and various elements for purifying and buffering the water.
- Divert the rainwater through aboveground gutters surrounding the buildings of the new city districts as part of public space design.
- Build permeable pavements to reestablish a more natural hydrologic balance and reduce runoff volume by trapping and slowly releasing precipitation into the ground instead of allowing it to flow into storm drains and out to receiving waters as effluent.
- Build bioswales to slow and reduce stormwater runoff while removing debris and filtering out pollutants.
- Build rain gardens to collect and hold rainwater from downspouts, driveways, and sidewalks for a short time, allowing the water to slowly seep back into the ground.
- Implement 'green space factor' as an instrument to guarantee a certain volume of greenery in residential courtyard and to ensure that green qualities are achieved in connection with the city's new construction projects.
- Use green space factor where appropriate.
- Monitor and improve the effects of green space factor pertaining to such ecosystem services as recreation, reduced risks of flooding, improved local climate, and noise reduction.
- Reinforce ecosystem services in urban various urban practices so that their benefits and functions do not deteriorate.
- Supplement the green factor system with green points, a list of a number of wide–ranging environmental measures, that can be implemented to promote biodiversity in the existing and new city districts.
- Transform the existing green and water views across the new city districts into liveable waterfront areas offering plaza, green space, and promenade, allowing for a variety of activities to take place and providing great opportunities for the social mix and interaction of the residents of the new city districts.
- Use the waterfront footpath as linkages to several landscape nodes.
- Create and distribute parks across the new city districts by ensuring 100% of the existing apartments have access to a park and natural environment within 200 meters, as well as by reserving a sufficient number of hectare for parks and dividing them between these apartments.
- Develop and implement advanced technologies for monitoring the condition and composition of green space in the city districts.
- Develop and implement new technologies to stimulate biological and ecological diversity and conservation.

3.3.2. Essential Urban Infrastructure: Smart and Sustainable Systems

As a wide-ranging term, infrastructure is the basic structure which supports the operation of a city. This makes economic and social development possible. The focus here is on the essential sustainable and smart infrastructures that make up the city, including transportation systems, communication systems, energy systems, waste systems, lighting systems, sewage systems, and waste disposal systems. These are associated with the basic facilities, services, and installations needed for the functioning of the city in terms of engineered systems. Worth pointing out is that the essential urban infrastructure embodies economic infrastructure, the internal facilities of the city that make business activity possible or promote economic activity, such as communication, transportation, distribution networks, and energy supply systems.

The essential urban infrastructure involves six key strategies:

1. Smart sustainable transportation
2. Smart sustainable energy
3. Smart sustainable waste management
4. Smart urban metabolism
5. Smart street lighting
6. Smart urban infrastructure

3.3.2.1. Smart Sustainable Transportation

To be able to effectively improve and strategically advance the contribution of the city to the goals of sustainability, it is necessary to fully integrate sustainable transportation system with smart transportation system. Accordingly, the smart sustainable transportation strategy encompasses seven substrategies, namely:

1. Walking and cycling
2. Public transport
3. Car-pooling (biogas and electric)
4. Electric vehicles

5. Smart transport management
6. Smart traffic management
7. Smart mobility management

Sustainable transportation: Sustainable transportation is a major strategy for achieving sustainability. It denotes any means of transportation that is green and has low impacts on the environment. Below are the key pathways for executing the sustainable transportation strategy.

- Implement the hierarchy of sustainable transportation, namely walking and cyclin, public transport, car pools, and private cars.
- Set clear targets for reducing car journeys with the long long–term objective of establishing the hierarchy.
- Provide a range of opportunities for walking and cycling through increased densities and short distances, i.e., proximity to workplaces, shops, services, and facilities in densely residential areas.
- Improve the public transport system by creating new connections, enhancing existing networks, and influencing habits and movements through soft measures.
- Improve the capacity, comfort, waiting time, and service quality of the public transport system.
- Build and enhance pedestrian paths/walking tracks and bike paths/cycle lanes linking different areas of the city districts to local workplaces, shops, businesses, and facilities.
- Build new cycle bridges linking the new city districts to the city center and the inner city.
- Make good availability of bicycle parking throughout the city.
- Provide incentives that give priority to cycling by offering a higher than average number of cycle parking spaces per apartment, house, and building.
- Restrict car parking by limiting parking spaces per apartment, house, and building.
- Close public spaces to cars and provide further opportunities for walking and cycling along pleasant routes.
- Provide incentives for electric and biofuel cars and taxis.
- Develop and implement strategic plans for the transition from private-owned cars to a plug-in hybrid, to mobility as a service with electric taxis, to biofuel diesel, and to public transport:
  - Private cars can be changed to a plug-in hybrid and then replaced by mobility as a service with electric taxis, a small alteration of self-driving electric taxis. An important precondition for the expansion of this traveling mode is the charging stations for electric cars that should be in place across the city.
  - Private cars can be changed to a biofuel diesel cars and then to public transport for everyday mobility and renting or sharing a biodiesel for longer trips.
  - Gradually increase the percentage of the private cars leaving the different districts of the city and allow a fleet of more and more self-driving electric taxis to circulate in these districts.
- Make buss stops within reasonable distance from blocks of building and with shortest possible running time intervals (e.g., operating on a five-minute schedule).
- Provide hassle–free usage of multiple modes of shared and public transport.
- Use biogas-fuel powered and hybrid busses as well as solar-powered screens showing times of arrival at bus stops.
- Combine measures and initiatives for shaping the physical structure of sustainable transportation as well as influencing behavior.
- Implement mobility management as a soft measure to build, develop, and maintain transport infrastructure and to create and keep the dialogue with different stakeholders as to how to make choices for travel modes.
- Introduce economic, social, and environmental policies through the congestion charges and Ultra Low Emission Zone (ULEZ), and allow the residents to tangibly see the impacts of automobile use across all three pillars of sustainability.

Smart Transportation: Smart transportation is one of the main ways modern cities can improve the daily lives of citizens and sustainability. It involves information systems that collect data about traffic, vehicles, and the use of different modes of transport for further processing and analysis in city operations center. Transport and traffic management is one of the most common areas that use data-driven technology solutions. The key pathways for executing the smart transportation strategy are:

- Develop and implement the unified public transport system with ticketing system.
- Develop and implement the bus transit system based on the orthogonal network of bus lines.
- Manage all the transport services of the city in real-time based on the data received from the situational centers.
- Develop and implement the smart traffic light system.
- Develop and implement the smart parking system.
- Encourage businesses and consumers to use vehicles equipped with telematics.
- Raise awareness of the options and benefits of intelligent transport systems.
- Apply disincentives to alter demand for carbon intensive vehicles. Equip public transport with advanced sensors to monitor mobility and movement and collect related data (e.g., precise geo-positioning, times, delays, number of passengers, etc.) for mining and visualization
- Use mobility and movement data for planning in terms of determining the need for launching new public transport routes or developing new road infrastructure.
- Implement the smart board for displaying information about the roads conditions in real time.
- Ensure seamless, efficient, and flexible multi–modal transport system.

- Support equity and inclusion using smartphone apps in sustainable urban transport.
- Develop and implement new business models for "Mobility–as–a–Service" for sharing systems.
- Develop and implement the bicycle sharing system for short trips across the city.
- Develop and promote smart apps for other modes of sustainable mobility to keep the citizens up-to-date and connected.
- Use sensed mobility data to understand how mobility behavior and traffic variation from one day to another is linked to the network topology for developing smart apps to influence travel behavior towards sustainable mobility.
- Integrate real–time mobility data and large–scale datasets that simultaneously record and calibrate dynamical traces of individual and collective movements across various spatial scales and over different temporal scales to understand the dynamic interplay between individual and collective mobility and social interactions.

3.3.2.2. Smart Sustainable Energy

The smart sustainable energy strategy aims to reduce energy consumption, increase renewable energy adoption, and decrease carbon footprint. Here technological innovations can play a prominent role in the light of the high predicted rate of urbanization. Integrating sustainable energy with smart energy will drive data-driven smart sustainable cities of the future to become fossil fuel–free and climate positive. Therefore, the energy system should combine green energy technologies and energy efficiency technologies. Accordingly, the smart sustainable energy strategy involves five key substrategies, with some overlaps among them, namely:

1. Renewable energy sources and technologies
2. Smart power grid and advanced metering infrastructure technologies
3. Smart building technologies
4. Smart home monitoring technologies
5. Smart environmental monitoring technologies.

The key pathways for executing the four last substrategies have already been addressed in (Bibri 2020e). This paper specifically provides the key strategic pathways for achieving the goals of energy efficiency and pollution reduction. The identified data-driven smart solutions are found to have significant potential to improve and advance environmental sustainability in the context of emerging smart sustainable cities.

Renewable Energy Sources and Technologies: It is important to strongly advocate renewable energy generation and usage in order to enable the city to become fossil fuel–free by 2050. Renewable energy is derived from naturally replenished and zero-emission sources such as solar, wind. biomass, hydropower, and geothermal), using a number of industrial and technological systems. Below are the key pathways needed for implementing the substrategy of renewable energy sources and technologies:

- Install solar collectors on the top of new and retrofitted buildings throughout the city to produce heat (see **Figure 2**).
- Install pumps (aquifer and sea water) to produce heat.
- Use aquifer and heat pumps for cooling.
- Combine solar collectors and pumps to aggregate heat production.
- Promote and install solar panels/photovoltaic cells throughout the city to produce electricity.
- Install stations of wind turbines to produce electricity for heat pumps as well as dwellings.
- Complement windmill farms by installing wind generators, smaller versions of massive power generators, in the different parts of the city districts.
- Perform solar thermal installations for energy monitoring to aid in understanding the solar thermal energy produced and consumed.
- Link diverse energy plants to the city's energy system for district heating, district cooling, and power grid.
- Build large scale bio–fueled combined heat and power (CHP) system for producing electricity and heat by renewables and organic household waste. The incineration of waste is used to produce energy for heating systems.

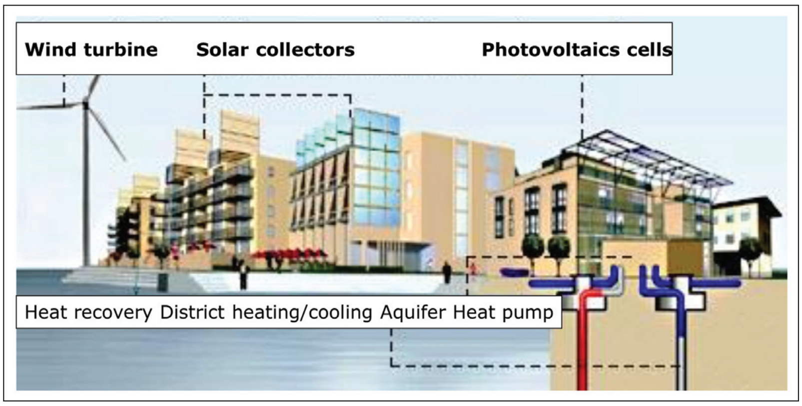

Figure 2: Heating and cooling based on renewables in Western Harbor District, Malmö, Sweden.

It is worth noting that some of the above installations depend on the geographical location and climate of the city as well as its energy needs. **Figure 2** illustrates an example of a renewable energy system integrating wind turbine, solar collectors, and photovoltaics cells for heating and cooling. Today, solar panels often cost less than on-grid electricity. Moreover, if all buildings' electricity is produced with solar energy, carbon emissions can be reduced by more than 50% compared to baseline in sustainable cities by 2030. Therefore, it is important to aim for shifting electric supply from 100% large-scale to 100% local solar power.

The main goal of the renewable energy sources and technologies strategy is to phase in renewables and phase out fossil fuels by 2050, resulting in 100% locally produced electricity and heat from clean sources in most districts and ultimately supporting the entire geographical area of the data-driven smart sustainable city of the future. This kind of transformational change requires a strategic roadmap, i.e., a time-based plan that defines a future outcome and determines and assesses the decisive steps needed to reach it.

3.3.2.3. Smart Sustainable Waste Management

To achieve far more resource-efficient use of waste that has minimal impacts on the environment requires developing and implementing a number of measures and solutions as part of smart sustainable waste management. This strategy encompasses seven substrategies, namely:

1. Convenient and smart waste collecting system
2. Vacuum waste chutes
3. Food waste disposers
4. Biogas digesters
5. Wastewater and sewage treatment system
6. Biological waste separation procedures

Sustainable waste management: The key pathways needed for executing the sustainable waste management strategy are:

- Standardize the planning of sorting facilities for separating packaging, food waste, and mixed waste, and ensure that all properties have access to these facilities.
- Build and evenly distribute large waste sorting stations throughout the city districts, and connect them to the city's waste infrastructure.
- Create and implement the relevant regulatory instruments with respect to waste management, and monitor progress to ensure the effective use in terms of the extent they yield desired results.
- Adhere to the waste hierarchy that reduces the quantity of the produced waste and the hazard it poses and prioritizes material-efficient products, thereby placing emphasis on recycling, reuse, and minimization of consumption in all its cycles.
- Use ICT to substitute for physical products.
- Design the waste sorting system in a way that is accessible and makes it easy for the residents to sort their waste in a safe and sustainable manner.
- Develop and disseminate easy-to-understand guidelines for sorting waste at the source.
- Ensure a high degree of waste separation in the city districts.
- Consider converting the food waste collected throughout the city districts into bio–fertilizer that can replace artificial fertilizer on agricultural fields.
- Build wastewater and sewage systems in the city districts, and integrate them in the city treatments plants
- Recognize that wastewater and sewage fractions are important energy resources (i.e., biogas fuels) and integrate them in the sustainable energy system.
- Develop and implement measures for influencing behaviors through engaging residents as part of environmental stewardship, as well as promoting sustainable habits and lifestyles.
- Set the following targets for sustainable waste management when planning new districts:
  - 100% of the kitchen of the dwellings have waste disposal units.
  - 100% of the properties have access to a vacuum waste chutes system in the residential courtyards that is able to transport non-organic waste underground.
  - Waste separation units are close to home for sorting paper and packaging materials, food waste, and mixed waste.
  - Wastewater and sewage treatment systems are installed and operate effectively in the city.
  - Closed eco–cycles function properly.

Smart Management of Waste Collection: Smart waste collection systems are becoming more and more widespread, and many cities across the globe are already implementing this solution in the city management programs. Typically, smart management of waste collection involves adopting data-driven resolutions intended to improve the efficiency of the city management, especially in relation to the city districts with no vacuum waste chutes systems. The key pathways for executing the strategy of smart management of waste collection are:

- Install smart waste collection system in the city districts:
  - Use sensors to allow to determine the degree of the fulness of waste containers, the level of the collected waste, independent of the nature of the recoverable waste.
  - Transmit the information received from these sensors via the mobile network to cloud storage for processing, analysis, and visualisation.
  - Use the obtained results to allow the sanitation workers to plan the collection routes of their waste disposal trucks in the real-time mode based on the degree of fullness.
- Implement the smart waste collection system where needed.
- Develop and implement the BigBelly solution.

3.3.2.4. Smart Urban Metabolism

As a model used for describing and analysing energy and materials flows in the city and their relationship with its infrastructure and activities, urban metabolism serves to maintain the functional and evolutionary states of the city as a socio-technical organism. Looking at the data-driven smart sustainable city of the future through a metabolic lens, a framework through which to successfully model the flows of its systems becomes of high importance and interest. This aids in understanding the relationship between human activities and the natural environment by studying the interactions of human systems and natural systems in the sphere of the city. Indeed, urban metabolism provides a platform through which the implications of the different dimensions of sustainability can be considered.

- Develop and implement a smart urban metabolism framework based on real-time data, high temporal resolution, high spatial resolution, and continuous visualization of materials and energy flows to different city stakeholders and at different social scales.
- Use multiple key performance indicators (KPIs) which need to be based on real-time data generation from heterogenous sources and to be fed back on five spatial scales (household, building, neighborhood, district, and city) on the relevant interfaces developed for different audiences.
- Use dynamic and high resolution meter data for the evaluation of energy consumption in households and buildings. This is to increase the level of detail in the evaluation results and ease the detection of deviations in the performance of structures.
- Find more effective and innovative ways to deal with the challenges, barriers, and issues pertaining to the smart urban metabolism framework:
  - Access to and integration of siloed data from the different owners of data.
  - Privacy to motivate people to be actively involved in providing data.
  - The technical issues related to sensor technology, big data analytics, and emission factors.
  - Shortcomings concerning the use of dynamic and high resolution meter data for the evaluation of energy consumption, data collection and management, preservation of personal integrity, and incentives to react to the given evaluation information.
- Use diverse communication tools and methods for behavioral change, including:
  - Sustainable human computer interaction (HCI);
  - Eco-visualization;
  - Augmented reality;
  - Computersand smartphones;
  - Persuasive technology; and
  - Climate pervasive services.
- Use data-intensive scientific methods for studying urban metabolism to provide harmonized indicators for environmental sustainability assessment and for quantifying GHG emissions of the city, as well as for urban planning and policy analysis.

3.3.2.5. Smart Street Lighting

The city-wide street lighting system provides tremendous opportunities for modern cities to collect huge amounts of data from urban environments and to transfer them to special centers for their subsequent processing and analysis for enhancing decision making associated with numerous uses and applications. This can be used to make urban living more environmentally sustainable and to enhance the quality of life for citizens. Street lighting is one of the most interesting pathway to using and exploiting the IoT and big data analytics in future cities. Thus, it can be expanded beyond what is originally used for. The key pathways needed for executing the strategy of smart street lighting:

- Develop and implement the smart street lighting system and integrate it into the city-wide lighting infrastructure to enable the use of numerous innovative solutions related to transport, traffic, mobility, air and noise pollution, parking, safety, public Wi-Fi, and so on.
- Leverage the city-wide lighting infrastructure in achieving ambitious environmental goals at a lower cost given the pervasiveness, high visual impact, and cost-effectiveness of the street lighting system, in addition to its connection to the smart power grid system.
- Replace the street lights across the city with LED-based lighting system together with an IoT-based sensor network for advanced programmable features related to energy and the environment.
- Use the smart street lighting system to reduce the operational costs and optimize the energy efficiency of public-lighting system, as well as to reduce the risk of traffic collisions.
- Use smart street lights for night-time cycling based on context-aware technologies.

3.3.2.6. Smart Urban Infrastructure Management

Advanced ICT will be focussed on defining critical problems and events that might emerge rapidly and unexpectedly across the city. Analysing and identifying such problems and events is of great importance to urban sustainability and resilience. The smart management of the essential urban infrastructure involves monitoring and controlling its structural conditions in terms of potential changes that can increase risks and hazards as well as compromise safety and quality. In this context, data-driven smart technologies and solutions tend to be mostly justified by the high significance of the natural resources such infrastructure utilizes or involves in its operation. The key pathways needed for employing the strategy of the smart management of urban infrastructure:

- Support smarter transport, electricity, water, waste, and lighting networks in ways that can optimize resource efficiency and reliability and achieve more benefits with less expenditure and investment.
- Develop and implement new technologies for enhancing incident management, improving emergency

response coordination, harnessing synergies between different components, minimizing risks, ensuring safety and service quality, and reducing operational costs.
- Develop and implement new technologies for coordinating activities between various operators and service providers of the essential urban infrastructures in regard to scheduling repair and maintenance in a more efficient and effective way.
- Relate sustainable and smart urban infrastructures to their operational functioning, operational management, and short-term planning through monitoring, automation, control, optimization, and improvements using advanced ICT, especially the IoT and big data analytics.
- Analyze and investigate longer term sustainable and smart urban infrastructure needs and demands up to 2050—and use new technologies to meet them in a timely manner.
- Use joined-up planning to develop and implement new urban intelligence and planning functions that generate the kind of structures, systems, and forms that improve and maintain the sustainability, efficiency, and resiliency of the city.

3.3.3. Social Infrastructure

Social infrastructure is the development and maintenance of the basic facilities combined that are necessary for human development. It is a subset of the infrastructure domain and typically includes assets that accommodate social services. These are provided by a city government, either through the public sector (or related entities) or the financing of private provision of services. A huge part of new digital technologies, innovative solutions, interactive platforms, and diverse forms of public-private cooperation have become of critical importance to overcome the social challenges and to bring about the needed transformations in a number of social domains that sustainable cities and smart cities are facing. This is at the core of the assets of the social infrastructure of the data-driven smart sustainable city of the future, particularly in relation to citizen participation, public safety, healthcare, and education and training. Other assets are part of the built infrastructure, the essential urban infrastructure, and the technological infrastructure, such as facilities, community support, housing, sewerage, water and wastewater treatment, transport, public space, recreation, and so forth. In a wider sense, the data-driven smart sustainable city of the future also has a variety of sustainable development institutions and competence centers whose mandate is improving social, economic, and environmental aspects. The role of political and civic institutions and urban centers lies in maintaining the planning, development, governance, and functioning of the city as a data-driven smart sustainable entity in the future. However, the social infrastructure focuses on three strategies:

1. Smart citizens: participation and consultation
2. Smart public safety
3. Smart healthcare

3.3.3.1. Smart Citizens: Participation and Consultation

The social infrastructure is about people. Therefore, the involvement of citizens in the management and planning of the data-driven smart sustainable city of the future using information systems is crucial to the progress towards its ultimate goal. Such involvement is associated with the adoption of the most important resolutions related to living, which intend to improve the level of satisfaction and increase the level of confidence and trust among citizens in the city administration. The strategy "participation and consultation" aims to stimulate citizens' interest in taking part in the planning and development of the city. Research, knowledge development, and experience feedback are important preconditions for solving complex challenges. The key pathways for executing the participation and consultation strategy are:

- Develop online platforms to engage citizens and make it easier for them to find out about different issues of planning and land use.
- Develop crowdsourcing platforms to address important city issues related to different areas.
- Establish a platform to enable citizens to influence their experience of the city by providing feedbacks and ratings.
- Create a platform where citizens can participate in the surveys organized by the city administration which can use the related data to adopt the resolutions in relation to the different domains of city life.
- Create a platform to engage more citizens in dialogue so as to gather input on their needs and demands (e.g., buss timing, playgrounds, parking lots, parks, ICT system reliability, and mobile coverage indoors), to evaluate all their suggestions, and to identify and solve important issues. Citizens can suggest ideas which can be put to a vote among the registered users of digital platforms for polls.
- Create a platform to enable citizens to communicate as well as track the status and control the execution of their complaints related to city issues.
- Create special portals to enable citizens to report the economic problems existing in the city in response to the adverse effects of urbanisation, pandemics, and disasters.
- Create diverse platforms to allow citizens to participate in urban technologies and policies, including:
  - Classrooms for learning about the uses and applications of and innovating in emerging digital technologies;
  - Entrepreneurial spaces for attracting startups and skilled innovators to create and promote new technologies;
  - Co-innovation centers for enabling close collaboration among different city stakeholders;
  - Participatory platforms for connecting city stakeholders to support decision-making processes; and
  - Democracy platforms for enabling citizens to discuss government proposals as well as submit their own.

- Create city councils for remote service provision by public agencies and mobile kiosks.
- Develop and implement new technologies which offer the prospect of ending the digital divide, provided that they do not open up other kinds of divides.
- Develop data-driven projects to identify public trends that can be considered when developing programs and initiatives for urban development.
- Support and strengthen the technologies that ensure widespread citizen participation through enhanced security measures and privacy mechanisms.

3.3.3.2. Smart Public Safety

It is highly important to develop a much deeper and more informed understanding of the risks, threats, and hazards surrounding the city. This requires a new set of data-driven technologies and collective decision-making processes. Data-driven approaches to urbanism enables understanding the city as strongly interlinked and coupled systems that generates unexpected and surprising dynamics. Emerging technologies are increasingly changing the nature of such dynamics by predicting them on multiple scales in terms of the properties and processes which stimulate change within the city system, thereby outsmarting it. The key pathways needed to execute the smart public safety strategy are:

- Use cutting-edge tools through established platforms to create awareness of situations, provide realistic scenarios for hazards, and strengthen resilience by integrating artificial intelligence, expert knowledge, and human experience.
- Make use of data-intensive science in decision-making processes with respect to natural disaster preparedness, responsiveness, and recovery.
- Monitor urban environments to inform authorities as well as alert citizens of potential risks, hazards, and vulnerabilities.
- Use environmental monitoring systems to track air pollution (e.g, harmful substances) in real time to prevent or mitigate adverse effects on public health.
- Use advanced simulation models to predict disease outbreaks and act accordingly to save lives and resources through taking preventive measures.
- Use data-driven approaches to hazard identification and risk assessment to provide immediate responses to potential threats.
- Use data-driven sentient computing to improve security by denying access to suspicious users to public places.
- Use data analytics to investigate transportation–related safety and health issues and inform the responsible public and private entities to make improvements accordingly.

3.3.3.3. Smart Healthcare

One of the key areas targeted by technological advancements and innovations is human health. Medical systems and healthcare services are at the core of the IoT and big data applications. Healthcare management is one of the areas where the highest level of technology development and adoption is observed. The use of data analytics and personal wearable devices in medicine for the diagnosis and treatment of patients is one of the most promising areas of applied data-driven solutions in modern cities. Therefore, the focus should be on the electronization of medical services to enhance the quality of healthcare provided to all citizens and thus their well-being, as well as to upraise the effectiveness and efficiency of health system management. This entails using advanced tools, powerful computational processes, and innovative systems, such as embedded sensors and actuators, database system integration, management and monitoring software, simulation models, and decision support systems. The key pathways for executing the smart healthcare strategy are:

- Inform citizens about new healthcare policies and medical discoveries and rapidly disseminate information about disease outbreaks.
- Use advanced analytics techniques to analyze and interpret the huge datasets on health to improve the outcomes of healthcare with respect to those conditions that play out over longer times.
- Implement applied data-driven solutions in medicine for diagnosis and treatment by actively involving healthcare institutions, medical agencies, think tanks, and biotechnology companies as partners.
- Implement applied data-driven solutions to influence legislators on changes in regulating the medical and pharmaceutical industry.
- Encourage public and private medical organizations to adopt big data technology in their activities in terms of the implementation of eHealth platforms to accumulate, store, and deliver access to information about citizen health and medical history. The state-of-the-art technologies of big data analysis can be used to:
  - Perform accurate forecasts of the load on medical services and activity planning;
  - Evaluate the efficiency of educational programs, the quality of the obtained data, and the level of satisfaction of employers; and
  - Conduct health trend analysis of citizens.
- Connect medical centers, doctors, and patients with health data repositories and management software programs and sensing and communication capabilities to optimize the efficiency and performance of healthcare systems in terms of monitoring, traceability, and accessibility.
- Employ monitoring medical devices to remotely detect anomalies, gather patients' behavioral information, detect changes in their normal parameters to help improve the quality of recommendations and the accuracy of diagnosis.
- Gather all information about human health and treatment in electronic health record (EMRs) to allow physicians from different medical institutions to access patients' medical records and to enable patients to participate fully in healthcare decisions.

- Gather and analyze information on health indicators from non-specific devices, such as bracelets, smart watches, and sensors, as well as special medical devices.
- Establish a situation center to monitor the availability of and demand for medical services by analyzing the amount of appointments to doctors.
- Define inspection priorities and schedules based on the analysis of data on health standards in terms of checking the condition of hospitals and procedures and the execution of business rules.
- Inspect the recipients of health benefits based on the analysis of data to determine the level of compliance.
- Develop and implement the unified medical information and analytical system for healthcare. Such system comprises communication center, electronic registry, electronic health record, electronic prescription, disability certificates, laboratory services, and personalized record-keeping. It allows combining a variety of medical services and digitally collecting and analyzing data.
- Set the following targets prior to implementing the large-scale system of electronization:
  - Increase the transparency of medical facilities for citizens.
  - Raise the trust of citizens in health care system
  - Reduce queues in polyclinics by collecting and analyzing information on the flow of patients and the demand for medical services using a system of electronic records to set up appointments.
  - Distribute workers and doctors in healthcare centers based on data-driven decisions.

3.3.4. Technological Infrastructure

Generally, an ICT infrastructure includes hardware, software, networking, data storage, as well as an operating system. These are used to deliver applied solutions to the different stakeholders of the city. The ICT infrastructure of the data-driven smart sustainable city of the future must be able to integrate numerous application domains for sustainability across various spheres of its administration. Vital elements in this regard are the IoT, big data analytics, and artificial intelligence. These are to be used and integrated in more innovative ways to solve the problems related to the city management.

The ICT infrastructure can be deployed within the city's own facilities or within cloud computing. The ICT infrastructure strategy includes the following substrategies:

- Sensor infrastructure and digital network for data transfer
- IT architecture layers
- Data sources and open data

The competencies associated with the ICT infrastructure pertain to the process of big data analytics in terms of generating, processing, analyzing, and visualizing data for enhancing decision making across the various domains of the city (transport, traffic, energy, environment, healthcare, public safety, etc.). They depend on the scale and quality of the instrumentation, datafication, and computation dimensions of the city. This in turn determines the nature and range of the solutions provided to optimize, enhance, and maintain the performance of the city with regard to sustainability. Digital instrumentation produces huge amount of data, which are transformed into datasets and thus become easily conjoined and shared and highly appropriate for handling. These datasets allow real-time analysis of the different aspects of urbanity to generate deep insights that can be used in decision-making processes and in developing simulation models for managing, planning, and designing more sustainable cities. The essence of digital instrumentation lies in coordinating and integrating technologies (and hence the strategies of sustainable cities and the solutions of smart cities) that have clear synergies in their implementation within development planning and operational management. This opens up and enables realizing many new opportunities in the context of sustainability. The key pathways needed for executing the ICT infrastructure strategy are:

3.3.4.1. Sensor Infrastructure and Wireless Network for Data Transfer

- Develop and implement measures for modernizing the infrastructure of the city to make it ready to integrate data-based management.
- Implement and exhaustively deploy the sensor infrastructure and increase the number of Wi-Fi hotspots to cover the city areas to form a dense network of sensors.
- Build and extend the city Wi-Fi to increase the communication capabilities of the sensors deployed across the city areas as well as the data transfer processes.
- Ensure the fastest rate of wireless networks across the city areas.
- Ensure that all citizens have access to the Internet.
- Provide free Wi-Fi to all public buildings and facilities.
- Prioritize affordable high-speed digital connectivity for the city and provide free Wi-Fi to all citizens.
- Digitize businesses and organizations and increase the number of people working in the technology and service sectors.

3.3.4.2. IT Architecture Layers

- Set the basics of the IT architecture defining the strategies and policies allowing the sustainable city to become a data-driven smart sustainable city. This endeavor should be based on the joint cooperation of the city government, ICT companies, and academic institutions.
- Design, develop, implement, and maintain the IT architecture of the data-driven smart sustainable city of the future based on three main layers, namely (1) the information layer, (2) the middleware layer, and (3) the application layer:

1. The information layer is based on the whole complex of data sources, data routinely generated

about the city and its citizens by a range of public and private organizations. This layer collects raw data from different sources within the framework of the data-driven smart sustainable city of the future. These sources include sensors, cameras, transponders, meters, actuators, GPS, transduction loops monitoring various phenomena, and computerized databases, as well as a multitude of smartphone apps and sharing economy platforms generating a range of real-time location, movement and activity data. This layer also includes technologies and solutions allowing the transfer of the collected data for their further processing and analysis. The sensor platform of this layer isolates the applications that are to be developed to exploit the information generated by the city of the future. It also provides openness and interoperability. The data infrastructure standardization and data integration in a unified system significantly simplify the further usage of data.

2. The middleware layer collects raw data from the information layer and standardizes them for further processing and analysis. It provides tools for the storage, processing, and analysis of the collected data, which allow interpreting data, making forecasts on their basis, and identifying interconnection between different data ranges. This set of data analytics techniques enables obtaining the meaningful information from the resulting vast deluge of real-time, fine-grained, contextual, and actionable data for numerous applications. It represents the operation system for the data-driven smart sustainable city of the future, a platform that offers a comprehensive and transversal connectivity to serve citizens and other stakeholders. It is an open-code IoT platform that is accessible and open for use by third parties to download, develop, and/or modify data.
3. The application layer is the set of applications that use the meaningful information made available from the lower layers, and that provides services for the data-driven smart sustainable city of the future. It serves for the exchange of data among all the interested parties and the adoption of solutions based on the obtained data. It is based on the idea of using data to predict situations in order to make better decisions and reactions. This layer includes platforms with open data and tools of data visualization (e.g., dashboards and smart board) applied by the city administration for control over the city management system, automated systems of response to city-wide events (e.g., situation centers and control rooms), as well as a plethora of application developers, including city governments, state agencies, and private developers.

The ICT infrastructure for the data-driven smart sustainable city of the future comprises a collection of smart solutions for various spheres of its administration. It includes novel applications and services for city agencies and departments to serve different stakeholders, and demonstrates the innovative use and integration of the IoT, big data analytics, and artificial intelligence to solve problems within the aforementioned domains of urban life.

3.3.4.3. Data Sources and Open Data

Data sources characterize the availability of the actually used and potentially to be used sources of data. Based on the analysis of these data, the data-driven smart sustainable city of the future will be able to make countless and support complex decisions pertaining to planning, design, and operational functioning. However, some data are open and thus accessible to the public for use, while other data are confidential and thus pose privacy issues. Also, some data are available virtually for free, while other data require effort to obtain. Still not all the data needed for the development and implementation of applied data-driven solutions for sustainability exist. However, the key pathways needed for executing the strategy of data sources and open data are:

- Support cooperation between the public and private sectors regarding the open data initiatives.
- Define rules and guidelines for the open data platforms to work with the public and private sector organizations:
  - Stimulate the publishing of dynamic data and the uptake of Application Programme Interfaces (APIs).
  - Limit the exceptions which allow public bodies to charge more than the marginal costs of dissemination for the re-use of their data. This involves the data held by public undertakings, under a specific set of rules in terms of the data made available for re-use.
  - Develop regulatory frameworks for open access to publicly funded research data. New rules should also facilitate the re-usability of research data already contained in open repositories.
  - Strengthen the transparency requirements for public–private agreements involving public sector information, thereby avoiding exclusive arrangements.
  - Identify and espouse a list of high-value datasets to be provided free of charge. These datasets have a high commercial potential and can speed up the emergence of value-added information products. They should also serve as key data sources for the development of Artificial Intelligence in relation to sustainability.
  - Develop ancillary projects in the form of organizations, institutions, and enterprises to arrange the collection and storage of data, providing the necessary support to the primary activities of the city stakeholders.
- Enable and promote common data standards (open, semi-open, proprietary, etc.).
- Develop and implement principles and measures to facilitate the integration of the different cross–thematic categories of data into coherent databases prior to large-scale data analytics. This relates to the public

policy domain of big data in terms of:
  - How to collect, store, and coalesce various types of data in the city data warehouse;
  - Which stakeholders should be involved within each of existing city domains;
  - What concerns are relevant for the diffusion of big data technologies and platforms;
  - How to exchange or make use of data standards;
  - How the residents should be involved in the decision–making process pertaining to the selection and deployment of big data innovations; and
  - The legal and ethical dimensions in terms of data access and control and privacy and security.
- Develop strategic initiatives related to data protection and regulation:
  - City data analytics office as a platform for sharing the information generated or stored by public bodies with individuals and organizations.
  - Data commons city as an open-source policy toolkit regarding ethical digital standards for the city to develop digital policies that put citizens at the center and make governments more open, transparent, and collaborative.
- Use open data to promote transparency and build trust in government decision–making and official policies.
- Develop mayoral institutions for the governance of big data for situating the application of related innovations and financially supporting critical urban datasets.
- Open up data to improve policymaking and to encourage innovation:
  - Make data publicly available for businesses and citizens to use, as well as provide tools for visualization and analysis.
  - Use data to inform the making of policies and decisions.
  - Make data available to the general public to drive innovation and collaboration in the development of new urban solutions, e.g., the formation of startups and the launching of new software applications to create economic and social value.

Up till now, the four models of sustainable urbanism and smart urbanism investigated are weakly connected as approaches and extremely fragmented as landscapes at the technical and policy levels. The compact city and eco-city models of sustainable urbanism, which have been around for over four decades or so, have many overlaps among them in their ideas, concepts, and visions, as well as distinctive concepts and key differences in terms of planning practices and design strategies. The overlap is justified by the fact that they both represent the central models of sustainable urban development Therefore, they are, to some extent, compatible and not mutually exclusive. As to the data-driven smart city, which is an emerging paradigm of smart urbanism, it shares the challenges of sustainable development with the two models of sustainable urbanism, with the main difference being that it focuses more on the use and adoption of data-driven technologies and solutions and related technical and institutional competences to overcome these challenges—than on the planning practices and design strategies of urban sustainability. Concerning the environmentally data-driven smart sustainable city model, it emphasizes the dimension of environmental sustainability and employs data-driven technology solutions to reach environmental targets. In this sense, this model combines concepts and ideas from both the eco-city and the data-driven smart city. The two models are increasingly being merged on the basis of the IoT and big data analytics technologies in a bid to overcome the significant challenges posed by climate change in the face of the escalating trend of urbanization. However, while both implement data-driven technology solutions to improve and advance environmental sustainability, they remain significantly divergent with respect to their priorities, values, visions, policies, strategies, and goals, thereby the meaningfulness of their integration in the fourth case study.

4. Discussion

The main outcome of this study is the strategic pathways developed to bring about the preferred future. This involves identifying a set of planning actions and policy measures that enable to build a data-driven smart sustainable city in terms of the built infrastructure, sustainable urban infrastructure, smart urban infrastructure, social infrastructure, and technological infrastructure of its landscape. Developing strategic pathways is at the core of most of the backcasting approaches applied in the futures studies that address the various topics of sustainability transitions, or deal with long-term problems and sustainability solutions. This study is concerned with a pathway-oriented category of backcasting (e.g., Bengston Westphal and Dockry 2020; Wangel 2011), which is about identifying the planning actions and policy measures that connect a desirable state of the future to the present. At the core of this category, in the context of this paper, is how to bring about changes to the landscapes of the data-driven smart sustainable city of the future through different, yet interrelated, transformations related to the compact, ecological, and infrastructural designs of the city. Such transformations are of a complementary nature in line with the requirements of the future vision. However, setting strict goals in perspective of this category is of less importance (Vergragt and Quist 2011; Wangel 2011) compared to the other categories of backcasting, such as action-oriented backcasting, target-oriented backcasting, and participation-oriented backcasting (e.g., Akerman, Höjer 2006; Höjer, Gullberg and Pettersson 2011; Quist et al. 2001; Wangel 2011).

We identified the key strategies and pathways needed to move from the current state of sustainable cities to the future state of data-driven smart sustainable cities. This new integrated model of urbanism provides an important planning tool for facilitating the endeavor to build various models of sustainable cities that respond to the ongoing shifts brought by big data science and analytics and the underlying enabling and driving technologies. This means allowing sustainable cities to enhance, optimize, and potentially maintain their performance in regard to supporting, balancing, and integrating the three dimensions of sustainability thanks to emerging and future data-driven technologies and their uses and applications in many urban domains and across several spatial scales. The construction of the vision of the future based on broadly defined objectives and targets is about setting priorities, incorporating values, and adopting principles pertaining to sustainability while taking advantage of what the multifaceted potential of advanced ICT through its innovative solutions for a large number of sustainability areas. This has indeed been demonstrated by several studies addressing the environmental, economic, and social aspects of sustainability (e.g., Angelidou et al. 2017; Bettencourt 2014; Bibri 2020b; Bibri and Krogstie 2017b; Kramers, Wangel and Höjer 2016; Nikitin et al. 2016; Pasichnyi et al. 2019; Thornbush and Golubchikov. 2019; Trencher, G. 2019; Shahrokni et al. 2014; Shahrokni, Levihn and Brandt 2014) through innovative operational management mechanisms and enhanced development planning practices.

The technological facets of the futures study have been addressed in more detail in the two case studies conducted on the emerging paradigms of smart urbanism. One of the key aspects to highlight in this regard is the role of smart cities in connecting the aforementioned infrastructures associated with the transformations needed to attain the future vision through the identified strategies and pathways. This connection, as enabled by advanced ICT as essentially network-based, is a way to leverage the collective intelligence of the data-driven smart sustainable city of the future through the synergic nature of ICT in regard to producing the tripartite benefits of sustainability. In other words, in making sustainable cities cleaner, safe, and more efficient through the new urban intelligence functions enabled by joined-up and short term planning approaches. This can be accomplished by harnessing the vast troves of data that can be generated from across many urban domains thanks to advanced computational analytics techniques as well as urban operation systems and analytical centers (e.g., Batty et al. 2012; Bibri 2019b; Kitchin 2014, 2016; Kitchin, Lauriault and McArdle 2015; Nikitin et al. 2016). Sustainable cities involve the kind of challenges that are enormous enough to call for a data-driven approach to planning as a function of many diverse city stakeholders. Joined-up planning is a form of integration and coordination that enables the city–wide effects associated with environmental, economic, and social sustainability to be monitored, understood, and embedded into the designs and responses of sustainable cities in terms of their operational functioning, I.e., forms, structures, spacial organisations, activities, and services as embedded in space and time.

The compact and ecological facets of the futures study characterize sustainable cities in terms of urban design. While the environmental goals of sustainability tend to dominate in the discourse of the eco-city (e.g., Mostafavi and Doherty 2010; Holmstedt et al. 2017), the discourse of the compact city emphasizes the economic goals of sustainability (e.g., Hofstad 2012; Jenks and Jones 2010), with the social goals of sustainability being of less focus in the eco-city than in the compact city (see, e.g., Bibri 2020b, c; Lim and Kain 2016; Heinonen and Junnila 2011; Bramley and Power 2009; Raporport and Verney 2011). In view of that, it is of significant importance to integrate both models of sustainable urbanism so as to strengthen their design strategies and green technology solutions to deliver the best outcomes of sustainability. Several studies have supported the idea that the compact city has the ability to support and balance the three dimensions of sustainability (e.g., Bibri, Krogstie and Kärrholm 2020; Burton 2002; Dempsey 2010), but it needs to strengthen the influence of the environmental and social goals of sustainability over urban planning and development practices (e.g., Bibri 2020c; Hofstad 2012). The ultimate goal is to create sustainable cities that can contribute to resource efficiency and reliability, environmental protection, socio-economic development, social cohesion and inclusion, the quality of life and well-being, and cultural enhancement. In fact, the two models tend to overlap in their principles, priorities, objectives, policies, and visions. In short, they are not mutually exclusive. Other attempts undertaken in this direction represent ideal approaches with inherent limitations of practical implementation (e.g., Roseland 1997; Harvey 2011). Farr (2008) discusses an integrated approach combining some elements of eco-cities, some elements of compact cities, and sustainable urban infrastructure. However, this approach lacks empirical basis and is not grounded in specific planning actions and policy measures for implementing it in a real-world setting. Kenworthy (2019) focuses on strengthening the eco-city through a number of urban sustainability principles related to deign, strategic planning, and transport.

The idea of integrating the two models of sustainable urbanism in question is based on fully merging their dimensions and strategies, with some flexibility concerning what to emphasize in urban planning and design and how this can be done depending on the characteristics of the urban areas that demonstrate the potential for future development. The novelty of this integrated approach to sustainable urbanism lies in incorporating sustainable energy systems, waste management systems, passive and low-energy buildings, and green structure in the built environment of the compact city to enhance its contribution to the environmental goals of sustainability. This is predicated on the assumption that these structures create the infrastructure needed to provide the ecosystem services and natural environmental processes, which can bolster compaction strategies to achieve better outcomes.

The nature of the integration of sustainable cities and smart cities is to be determined by the way in and the extent to which the dimensions and strategies of the former are pertinently extended and strengthened by those of the latter in the sense of creating a consolidated approach to data–driven smart sustainable urbanism that harnesses the synergistic effects and boosts the benefits of sustainability while supporting the balancing of its dimensions. This depends on the level of progress and how this can be assessed in regard to the different areas of sustainability within a given city that is badging or regenerating itself as sustainable or sustainable smart. Regardless, underlying the data-driven smart sustainable city of the future is the idea of its conception as processual outcomes of urbanization (building, living, consuming, and producing), rather than as stable unchanging structures. Indeed, the model of the city is no longer predicated on the basis of this conception—rather, it is as much dominated by information flows as material flows. Besides, sustainable cities as complex systems evolve and change dynamically as urban environments in response to emergent proprieties and factors. Accordingly, cities need to be processual in conception, dynamic in planning, scalable in design, and optimisable in operational functioning in order to be responsive to population growth, environmental pressures, changes in socio–economic needs, discontinuities, and societal transitions. And the best way forward is to adopt advanced technologies to deal with the complexities inherent in their development planning and operational management.

Sustainable cities growing ever bigger in terms of their populations and knowledge base lie at the core of the future model of urbanism. ICT will be most clearly demonstrated in large sustainable cities. Building sustainable cities enabled by big data technologies is increasingly seen as a strategic move for containing and tackling the rather mounting challenges of sustainability in the face of the expanding urbanization. This is justified by the influence these advanced technologies can have on the way we control, manage, regulate, govern, and plan sustainable cities. In particular, while planning cannot reproduce the compact and ecological characteristics of sustainable cities that have been developed based on incremental and interactive processes involving many stakeholders over time, the primary role of big data lies in enabling information flows and channels, coordination mechanisms, powerful analytics, well-informed and evidence-based decisions, and learning and sharing processes involving divergent constituents and heterogenous collective and individual actors as data agents. These are indeed the most significant challenges that are currently facing sustainable cities, coupled with the dispersion of power. These complex conditions are continuously exacerbated by the unpredictability of environmental, socio-economic, and demographic changes.

However, sustainable cities are so characterized by their specificities as regards their compact and ecological dimensions and how and the extent to which these are integrated in a given city area or district. This in turn shapes the way in which the IoT and big data technologies can be embedded in the fabrics of sustainable cities, as well as how they can be applied in their operational management processes and development planning practices. In more detail, sustainable cities essentially exhibit key differences in the way they prioritize and implement their strategies and solutions depending on many intertwined factors, notably physical, geographical, socio–political, economic, environmental, and historical. In particular, the IoT and big data technologies might work in one sustainable city in a way that is different in another. Hence, they should sometimes be dramatically reworked to be applicable in the context where they are embedded. Besides, sustainable cities do not have a unified agenda as a form of strategic planning, and data-driven decisions are unique to each sustainable city, so are environmental, economic, and social challenges. Big data are the answer, but each sustainable city sets its own questions based on what characterize it in regard to visions, policies, strategies, pathways, goals, and priorities. Regardless, it is important for sustainable cities to make the best use of their local opportunities and capabilities as well as to assess their potentials and constraints from a more integrated perspective when it comes to the operational management and development planning related to their compact, ecological, and technological landscapes and approaches.

In view of the above, the new model of urbanism is not meant to be universal in its nature, and it follows that the proposed strategic planning process of transformative change towards sustainability should look at the wider picture and be flexible in its means. In this respect, it is important to acknowledge the fact that universal urban models, whether compact, ecological, smart, or a combination of these, are problematic and cannot be applicable in the same manner all over the world (see, e.g., Bibri and Krogstie 2020c; Hofstad 2012; Karvonen, Cugurullo and Caprotti 2019; Rapoport and Vernay 2011; van Bueren et al. 2011). Therefore, urban models should be adapted to the multidimensional context specific to each city. In addition, while automation, big-data analytics, and artificial intelligence can bring numerous advantages to sustainable cities, it is equally important to acknowledge the fact that these advanced technologies can be problematic, and therefore, policy-makers and planners should be careful when employing them. Many recent studies have discussed the potential urban problems and issues triggered by automation, big-data analytics, and artificial intelligence in the context of smart sustainable urbanism (e.g., Bibri 2019a, c; Cugurullo 2020; Yigitcanlar and Cugurullo 2020).

5. Conclusion

Working with long–term images of the future is meant to increase the possibilities and stimulate the opportunities to attain the kind of sustainable cities that last thanks to emerging and future technologies. Sustainable cities are always about citizens. Being data-driven smart about sustainable cities requires to connect directly to the concerns and feelings of people with respect to environmental protection, economic regeneration, and social justice. Historically, people have always moved to and preferred to live in sustainable cities to improve their lives, and smart urbanism is being embraced anew as a strategic move to create sustainable cities that make urban living more sustainable over the long run. Towards this end, sustainable cities have to learn faster and identify strategies that work. Therefore, it is scholarly worthy to venture some thoughts about where it might be useful to channel the efforts now and in the future in what has been termed "data-driven smart sustainable urbanism."

This paper developed a novel model for data-driven smart sustainable cities of the future, and in doing so, it offered a strategic planning process of transformative change towards sustainability in the era of big data. It identified a series of actions and measures pertaining to the built infrastructure, sustainable urban infrastructure, smart urban infrastructure, social infrastructure, and technological infrastructure of the landscape of the data-driven smart sustainable city of the future. This empirically grounded model of urbanism is meant to be clearly specific in terms of the underlying components based on the prevailing paradigms of sustainable urbanism and the emerging paradigms of smart urbanism. The essence of this new integrated model lies in providing the needed tools, techniques, methods, systems, platforms, and infrastructures enabled by the core enabling and driving technologies of the IoT and big data analytics for the current model of urbanism to optimize, enhance, and maintain its performance with respect to the contribution to and balancing of the goals of sustainability.

In terms of the practicality of the new model of urbanism, the feasibility of the future vision is underpinned and increased by the outcomes of the four case studies The case study approach as a research strategy facilitates the investigation and understanding of the underlying principles in the real-world phenomena involved in the construction of the future vision in the futures study (Bibri 2020d). This pertains to:

- The extent to which the compact city and the eco-city support the balancing of the goals of sustainability
- The design strategies of the compact city and the environmental design and technology solutions of the eco-city
- The practice of the data-driven smart city in regard to the development and implementation of innovative applied solutions for development planning and operational management to improve and advance sustainability
- The role and potential the emerging data-driven technology solutions have in improving and advancing environmental sustainability within the frameworks of sustainable cities and smart cities.

The suitability of backcasting for the kind of problems that are associated with sustainable cities in terms of their contribution to and balancing of the goals of sustainability stems from the problem-solving and goal-oriented character of backcasting that is embedded in its process of strategic planning. Backcasting is useful in studying problems that are complex and associated with persisting trends that contribute to the problems' complexity. Moreover, it allows to imagine the impacts of the future vision, which should be highly significant and entail extensive and ambitious improvements and advancements compared to the current trend. The advantage of using this framework lies in its foundation and efficacy with regard to providing insights into and developing pathways for sustainability transitions, as well as in its ability to produce desired outcomes. This is of high relevance and importance to policymakers as to informing strategic plans for achieving the objectives of sustainable development and thus making actual progress towards sustainability. Here, backcasting can be viewed as a process of transformative change in the sense of how sustainable cities can be designed and developed so that they become able to monitor, understand, analyze, and plan their infrastructures more effectively so as to enhance and maintain their performance with respect to their contribution to sustainability in terms of its tripartite value. All in all, the new model of urbanism can be seen as an important arena for sustainability transitions in the era of big data. It offers a clear prospect of instigating a major transformation by synergistically connecting the agendas of urban development, sustainable development, and technological development for a better future.

Competing Interests

The authors have no competing interests to declare.

Author Contributions

S.E.B. designed the research, conducted the literature review, collected and analyzed the data, and wrote the manuscript. J.K. reviewed the manuscript. The authors read and approved the published version of the manuscript.

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EDITORIAL

Data-driven environmental solutions for smart sustainable cities: strategies and pathways for energy efficiency and pollution reduction

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Introduction

The concentration of economic activities, the high-intensity use of resources, and the massive deployment of non-renewable energy in cities demonstrate that they have major negative impacts on the environment. In other words, the significance of the environment in cities is justified by the fact that they consume about 70% of global energy supply, generate about 75% of greenhouse gas (GHG) emissions, and have currently more than 50% of the world population, estimated to reach 70% by 2050. In the current climate of unprecedented urbanization and increased uncertainty in the world, it is becoming increasingly more challenging for cities to configure themselves more sustainably from an environmental perspective (Bibri 2020a, b). Urban growth raises a variety of problems that jeopardize the environmental sustainability of cities as it puts an enormous strain on urban systems and thus great demand on energy resources and services. Energy produces the largest share of the world's emissions of greenhouse gases (GHG), which makes it the dominant contributor to climate change. With rising GHG emissions, climate change is occurring at rates much faster than anticipated and its effects are clearly felt worldwide (UN 2019a). The SDG 13 aims to take urgent actions to combat climate change (UN 2019b), which largely relate to the energy domain of cities.

Nonetheless, modern cities play a leading role in strategic sustainable development and have a central position in developing and applying advanced technologies to support the progress towards environmental sustainability in the face of the escalating urbanization trend. The United Nation's 2030 Agenda regards advanced information and communications technology (ICT) as a means to protect the environment, increase resource efficiency, achieve human progress and knowledge, and upgrade legacy infrastructure (UN 2015a). Therefore, the multifaceted potential of the smart city approach has been under investigation by the UN (2015b) through their study on "Big Data and the 2030 Agenda for Sustainable Development." This is of high importance and relevance to the Sustainable Development Goal 7 (SGD 7) of the UN's 2030 Agenda (UN 2019b): "ensure access to affordable, reliable, sustainable, and modern energy for all" (UN 2019a). Energy is at the core of sustainable development goals, and thus the modernization of energy systems is more needed than ever.

Currently, greater importance is given to economic development and social development at the cost of environmental integration and protection. In recent years, major topics discussed in this area have included the depletion of non-renewable resources, the harvesting of renewable resources, the destruction of ecosystems, and the generation of pollution. Therefore, advanced computational data analytics approaches are required to observe and discover hidden patterns of energy production and consumption in order to devise more effective solutions that could avert the multi-dimensional effects of devouring energy. There is a general consensus and practical evidence that data-driven technology solutions play a key role in improving energy efficiency and reducing pollution in both sustainable cities and smart cities (e.g., Bibri and Krogstie 2020a) within the framework of smart sustinable cities. Indeed, big data technology is seen as a critical enabler for advancing environmental sustainability given its unique ability to make energy consumption and GHG emissions visible through its processes, products, and services. Big data analytics techniques are gradually replacing the traditional mechanisms of urban management, with the aim to improve the quality and speed of decision-making

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pertaining to a wide range of practical uses and applications thanks to real-time analysis. Big data technology has become as essential to the functioning of smart cities (e.g., Angelidou et al. 2017; Bibri 2019a, 2020a; Bibri and Krogstie 2020b; Kumar and Prakash 2016; Nikitin et al. 2016) as to that of sustainable cities (e.g., Bibri 2018, 2019b, c, 2020a, b; Bibri and Krogstie 2020c; Shahrokni et al. 2014; Shahrokni, Levihn and Brandt. 2014; Shahrokni et al. 2015a; Shahrokni, Lazarevic and Brandt 2015) in the endeavor to optimize and enhance their performance with respect to environmental sustainability. This relates to what has recently been termed "environmentally data-driven smart sustainable cities" (Bibri and Krogstie 2020a) where the vision of smart energy and smart environment has spurred the development of new approaches to smart energy systems and environmental control and monitoring systems.

Resource efficiency and climate responsibility strategy and its substrategies

One of the overarching strategies of the leading environmental programs for smart sustainable cities is "resource efficiency and climate responsibility." (Bibri and Krogstie 2020a, c) With this strategy, smart sustainable cities aim to reduce GHG emissions to a level below 1 ton per inhabitant by 2030 and to become fossil fuel-free and climate-positive by 2050 as ambitious environmental goals. At the core of this strategy is the reduction of energy consumption and carbon footprint as well as the use of digitalization and new technologies to make it easier for citizens and businesses to be environmentally friendly.

Both smart cities and sustainable cities are increasingly investing in and implementing smart meters, sensor networks, automated control systems, and cyber-physical systems in the area of smart energy and smart environment within the framework of the Internet of Things (IoT). The main four substrategies of the resource efficiency and climate responsibility strategy associated with smart energy and smart environment are detailed next.

Smart grid and advanced metering infrastructure

The goal of smart energy is to achieve energy systems that are highly energy efficient, increasingly powered by renewable and local energy sources enabled by new technologies, and less dependent on fossil fuels. The main players in the area of smart energy are smart power grid and advanced metering infrastructure (including smart meters). Smart power grid denotes a set of hardware, software, and network tools which enable generators to route power more efficiently to consumers, reducing the need for excess capacity and allowing two-way communication for real-time demand side management. It collects the data received from the Wi-Fi-enabled sensor network on the level of power supply from diverse sources and then processes and analyzes these data in real time for decision-making and information transmission for process control to improve the performance of the power grid. Advanced metering infrastructure denotes a composite technology which consists of solid-state meters capable of remotely providing consumers' electricity use detail (i.e., electric energy, voltage levels, current, power factor) to the utility, a two-way communications channel (i.e., to power suppliers for system monitoring and billing and to consumers for greater clarity of consumption behavior), and a meter data repository and management. Thus, it includes sensors placed on consumers access points and on production, transmission, and distribution systems, as well as remote controls and communication technologies within electricity networks. The operational functioning of the smart grid system involves ICT system integration, data, and back office, which allow the integration of front-end engineering, middleware, and computing systems, as well as data collection and decision analytics (Bibri 2020b). This is part of the overall IoT infrastructure of smart sustainable cities in terms of horizontal information system and operations center. Typically, the operations center serves to monitor the city as a whole; to draw together real-time data streams from many different city agencies and departments into a single hub; and to process, visualize, and monitor the vast deluge of live service data for real-time decision-making and problem-solving. It includes automated systems of response to city-wide events (e.g., control rooms) pertaining to energy and environment, among others.

The key pathways (or tactics) needed for executing the smart grid and advanced metering infrastructure strategy—integrating and coordinating renewable energy production and consumption and power facilities through enabling technologies, energy services, and active users—are:

- Support projects of smart grid technologies.
- Subsidize projects that support energy-efficiency technology adoption.
- Allow decentralization of energy production.
- Encourage energy production from renewable sources.
- Promote the multiplication of grid distribution networks.
- Subsidize projects that incorporate integrate renewable energy in power distribution networks.
- Develop and implement integrated renewable solutions which involve the use of modelling, simulation, analytical, and management tools to enable a wide deployment of renewable energy.

- Deploy and Implement a large-scale smart grid system:
  - Smart homes/buildings and demand response.
  - Distributed energy systems.
  - Energy storage for the grid and consumers.
  - Smart primary substations.
  - Smart grid as part of innovation lab.
  - Integration and use of electric vehicles.

Smart buildings

The building management system (BMS) is primarily intended to maintain predefined parameters (or set points) and the control of their functionality. It uses smart metering and advanced visualization tools to provide real-time monitoring and continuously gather the data on what is taking place in a building and how its equipment is operating and feeding them into a control system to optimize performance. So, the collected data can be used to identify additional opportunities for energy efficiency improvements. Below are the key pathways needed for executing the smart building strategy:

- Subsidize design projects that support efficiency technology adoption and expansion among building owners and operators as well as urban developers.
- Reward the best-in-class buildings' owners and operators as well as urban developers.
- Provide funding schemes that encourage owners to invest in building automation systems.
- Develop and implement assessment tools for energy-efficient building.
- Regulate the use of automation measures in the construction of buildings and new development projects.
- Use decision-support systems which enable large-scale energy efficiency improvements in existing building stock.
- Evaluate the energy efficiency potential of different building vintages in collaboration with utility companies in the different districts of the city to reduce energy use, depending on the market segmentation pertaining to the date of the construction of buildings.
- Use data-driven smart approach to strategic planning of building energy retrofitting, using data about actual building energy consumption, energy performance certificates, reference databases, and so forth. This allows a holistic city-level analysis of retrofitting approaches and strategies thanks to the aggregated projections of the energy performance of each building, such as energy saving, emissions reduction, and required family or social investment.
- Install BMS in new and retrofitted municipal, commercial, and industrial buildings to monitor and optimize the use of the supervised subsystems.

Smart home appliances and devices

Smart homes allow homeowners to control appliances, lights, and other devices remotely using a smartphone through an internet connection. Smart home technology provides homeowners with convenience and cost savings. A smart appliance or device includes the intelligence and communications to enable automatic or remote control based on user preferences or external signals. The key pathways needed for executing the smart home appliances and devices strategy are:

- Promote and install energy star heating, ventilation, and air conditioning (HVAC) systems in municipal, commercial, industrial, and residential buildings.
- Promote and install energy star appliances which use a great deal less power than their predecessors.
- Promote and install smart power strips which sense energy demand and cut off power supply to fully charged or not in use devices.
- Promote and install smart meters to allow:
  - Consumers to manage their energy usage based on what they actually need and afford by having access to live energy prices and adjusting their usage accordingly.
  - Consumers to remotely control their home appliances and devices by means of such advanced functions as scheduling, programming, as well as reacting to different contextual situations.
  - Self-optimize and self-control energy consumption through integrating sensing and actuation systems in different kinds of appliances and devices for balancing power generation and usage.
  - Provide insights into how the energy flows can be influenced by the consumer behavior thanks to the in-house sensors that can provide data on energy-using appliances.
- Promote and install easy-to-use home energy monitoring systems (HEMS) which present useful information on energy usage directly to the consumer's devices, allowing them to change their behavior as well as save money in the long run. HEMS also offer homeowners more options than smart meter-to-smart appliance connections, e.g., a sophisticated level of preprogrammed preferences in terms of turning on some appliances based on the amount of the energy consumed within a day, week, or month.

- Promote and install energy monitoring software on smartphones in case the smart meter is already installed in the house so as to allow one to read the information collected by the smart meter.
- Install energy monitoring systems in municipal buildings for obtaining information about energy consumption, such as electricity meter, electricity ambient conditions, internal ambient conditions, and temperature.

Environmental control and monitoring

Air pollutants as atmospheric substances—especially anthropogenic—have negative impacts on the environment, as well as pose a high environmental risk to human health, so too is noise pollution, both direct and indirect. Noise pollution denotes harmful outdoor sound with road traffic being the greatest contributor. The demand for the smart systems that monitor the quality of the environment has increased because of the elevation of pollutants in the atmosphere The escalating urbanization trend leads to the environmental degradation of the air. Nonetheless, new technologies allow a real-time tracking capability of the different substances spread in the air, as well as applying preventive measures in a timely manner. For smart cities and sustainable cities to have the best air quality, they must significantly reduce GHG emissions from their energy and transport domains and become zero-carbon. One of the significant objectives of smart sustainable cities is to achieve a healthy and hyper-connected cities with zero emissions where urban planning, the environment, and ICT infrastructures are fully integrated and chracterized by productive neighborhoods (Bibri and Krogstie 2020a). Many recent studies address the impacts of energy consumption on the environment and on control over transport flows and their effects on the noise level (e.g., Angelidou et al. 2017; Bibri 2020a; Bibri and Krogstie 2020b; Nikitin et al. 2016).

Important to note is that the environmental monitoring strategy is complementary to the smart grid and advanced metering infrastructure strategy, which is indeed designed to control GHG emissions. Smart environmental control systems in smart sustainable cities can help to collect critical information to make better policy decisions to reduce GHG emissions. They can also guide citizens on making their own efforts to reduce GHG emissions. However, the key pathways needed for executing the environmental control and monitoring strategy are:

- Develop and implement more effective mechanisms to get consumers and producers to use innovative solutions to reduce GHG emissions to levels that are economically, environmentally, and socially sustainable.
- Develop and implement environmental control systems associated with energy efficiency (e.g., smart meters, smart sensors, automation devices, monitors, etc.).
- Develop and implement environmental control measures for preventing GHG emissions.
- Convert the small-scale tests performed in the areas of air pollution and noise pollution into pilot projects and then transition to large-scale deployments and implementations.
- Devise and implement solutions for control over air pollution which analyze the data collected from sensors on the level of air pollution in the different districts of the city.
- Develop and implement different prevention systems, including monitoring, forecasting, and modelling based on artificial neural networks, i.e., computing systems inspired by biological neural networks and based on a collection of connected nodes called artificial neurons, for enhancing decision-making to remove different types of pollutants detrimental to public health.
- Facilitate the operation of the air quality monitors by regulatory agencies, citizens, as well as researchers to investigate the air quality and the effects of air pollution.
- Devise and implement solutions for noise pollution control which analyze the data collected from sensors on the level of noise pollution for planning of work to reduce it. Such solutions should enable to optimize and centralize the collection, integration, processing, and dissemination of information by the noise sensors of different suppliers and sound level meters distributed throughout the city. The fine-grained information of noise can inform people's daily decision-making as well as policymakers on tackling noise pollution.
- Use the data recorded by the various sensors connected to the city's Wi-Fi network and reporting in real time such parameters as air quality, noise levels, temperature, humidity, and gas dust particles concentrated in particular urban environments to analyze the impacts of the measures taken to improve the state of the environment, to make inferences about the quality of the air, to compile further programs for environment protection, and to identify the areas where further actions are to be undertaken.
- Create living labs for environmental monitoring management which provide a variety of services by using sensors to measure a range of physical parameters. The active sensors recording the relative and appropriate information for the services should be spread across the different zones of the city for obtaining the accurate data for these services. Use the collected data to increase the knowledge of the most important city problems that need to be solved.

- Develop and implement an integrated automated environmental protection system in the city. The results of measurements should be published in online platforms to be visited by special software developers on a monthly basis.
- Promote easy to use and set up hardware and software for environmental monitoring systems (sensors and base units) among businesses, organizations, and institutions to:

  - Measure and log a range of environmental conditions (e.g., relative humidity, temperature, differential pressure, pressure, flow, lux, and carbon dioxide) in real time.
  - Track and provide early warnings in case of critical events or unfavorable conditions before they turn into disasters.
  - Provide various solutions for environmental monitoring with regard to server rooms, data centers, storage facilities, and laboratories to organizational and institutional units, as well as to those related to the ICT infrastructure of the city, such as horizental information platforms, analytical centers, and operations centers.

- Commit to further developing and advancing environmental monitoring technologies and enhancing their applications in the future to guarantee a maximized effect of the use of the information collected about the state of the environment. This is due to the challenges of enacting environmental monitoring, notably the effective integration of multiple environmental data sources originating from different environmental networks and institutions. Such integration requires specialized observation equipment, tools, techniques, and models to establish air pollutant concentrations at different spatial and temporal scales.

Summary

Data-driven smart solutions have significant potential to improve and advance environmental sustainability in the context of smart sustainable cities, notably smart grid, advanced metering infrastructure, smart buildings, smart home appliances and tools, and smart environmental control and monitoring. There is a clear synergy between these solutions in terms of their interaction to produce combined effects greater than the sum of their separate effects with respect to the environment.

Smart grid technologies provide numerous benefits associated with energy use optimization, energy management, energy conservation, cost reduction, as well as the integration of alternative energy sources in power generation, transmission, and distribution systems. They allow bidirectional energy flows and information between suppliers and consumers and provide data on real-time usage and energy pricing. This in turn provides numerous advantages, including real-time visibility, service reliability, control of cost and electricity usage, shift in peak load, capacity requirement of the grid, and energy production and sharing (prosumer). Similarly, smart building technologies have proven to be effective in curbing energy consumption. They can provide a multifunctional role in energy efficiency and GHG emission reductions through highly advanced automatic systems for efficient and natural lighting, temperature control, window and door operation, electric appliances, and many other functions. BMS allows more efficient operation, keeps the building's climate within a specified range, reduces energy consumption, reduces energy costs, and guarantees safety and security.

The different methods of collecting information about the quality of the air and the presence of harmful substances therein have recently undergone major advances thanks to the IoT. Related sensor systems are able in real time to gather data about the condition of the air in the different parts of the city and to transmit these data to special data analytical centers for processing and analysis. Moreover, it is possible now to produce a comprehensive analysis of the collected data, which allows the public authorities to observe the condition of the air and to forecast about its pollution on the basis of such analysis by means of sophisticated modelling and simulation systems. This is to effectively build a variety of preventive systems for environmental protection, as well as to inform citizens and other city stakeholders.

Policy plays an important role in addressing and overcoming the barriers to the development of smart grids, including the deployment of advanced metering infrastructure, as well as to the adoption of smart building technology. In fact, policy remains more important than technology in the context of smart sustainable cities. Most of the data-driven smart solutions that are being rolled out are only "plasters" that fail to address the wider environmental issues of climate change. This means that policy must be put into place to maximize the benefits of such solutions through more effective measures. Smart sustainable cities should have a set of specific policy frameworks to ensure that progress is made in any area of environmental sustainability where innovative solutions need to be implemented. Moreover, the new policy frameworks that aim to encourage or require the use of advanced ICT to mitigate climate change should be evaluated carefully in terms of their ability to absolutely reduce GHG emissions, not merely to slow down their rate of increase. Appropriate policy frameworks can provide the incentives needed to act and innovate to curb energy use and alleviate pollution levels. However, policy tools should include both incentives and prohibitions through a mixture of regulation, co-regulation, and self-regulation; top-down and bottom-up approaches to policy development and implementation; and governance arrangements that engage all stakeholders in their roles as citizens and consumers.

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Paper 13

A Novel Model for Driven Smart Sustainable Cities of the Future: The Institutional Transformations Required for Balancing and Advancing the Three Goals of Sustainability

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A novel model for data-driven smart sustainable cities of the future: the institutional transformations required for balancing and advancing the three goals of sustainability

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Abstract

In recent years, it has become increasingly feasible to achieve important improvements of sustainability by integrating sustainable urbanism with smart urbanism thanks to the proven role and synergic potential of data-driven technologies. Indeed, the processes and practices of both of these approaches to urban planning and development are becoming highly responsive to a form of data-driven urbanism, giving rise to a new phenomenon known as "data-driven smart sustainable urbanism." Underlying this emerging approach is the idea of combining and integrating the strengths of sustainable cities and smart cities and harnessing the synergies of their strategies and solutions in ways that enable sustainable cities to optimize, enhance, and maintain their performance on the basis of the innovative data-driven technologies offered by smart cities. These strengths and synergies can be clearly demonstrated by combining the advantages of sustainable urbanism and smart urbanism. To enable such combination, major institutional transformations are required in terms of enhanced and new practices and competences. Based on case study research, this paper identifies, distills, and enumerates the key benefits, potentials, and opportunities of sustainable cities and smart cities with respect to the three dimensions of sustainability, as well as the key institutional transformations needed to support the balancing of these dimensions and to enable the introduction of data-driven technology and the adoption of applied data-driven solutions in city operational management and development planning. This paper is an integral part of a futures study that aims to analyze, investigate, and develop a novel model for data-driven smart sustainable cities of the future. I argue that the emerging data-driven technologies for sustainability as innovative niches are reconfiguring the socio-technical landscape of institutions, as well as providing insights to policymakers into pathways for strengthening existing institutionalized practices and competences and developing and establishing new ones. This is necessary for balancing and advancing the goals of sustainability and thus achieving a desirable future.

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Keywords: Sustainable cities, Smart cities, Data–driven smart sustainable cities, Eco–cities, Compact cities, Institutional transformations, Sustainability dimensions, Data-driven solutions, Operational management, Development planning

Introduction

Cities are a mark of human civilisation and play a central role in the pursuit of new paradigms of thinking to bring about major transformations to the way people live and change the world in the process. Sustainability has, over the last four decades, been one of the most influential paradigms of thinking within urban development. Cities holding unparalleled potential to address and overcome the challenges of sustainable development largely depends on how they can be planned, designed, and managed, as well as on the extent to which they respond to new global trends and benefit from scientific discoveries and related technological advances. Appropriately redesigning and restructuring urban environments as sustainable cities and adopting innovative solutions to enhance and harness their strategies is a continuous endeavor towards achieving the long-term of goals sustainability.

Compact cities and eco-cities are the central paradigms of sustainable urbanism and the most prevalent and advocated models of sustainable cities. Numerous recent national and international policy reports and papers state that these two models contribute, though to varying degrees, to resource efficiency and reliability, environmental protection, socio-economic development, social cohesion and inclusion, quality of life and well-being, and cultural enhancement (Bibri 2020a). It is argued that the compact city model is able to contribute to and support the balancing of the three dimensions of sustainability (e.g., Bibri et al. 2020; Burton 2002; Jenks and Dempsey 2005; Hofstad 2012; Jenks and Jones 2010; OECD 2012), and that the eco–city model is able to achieve the goals of environmental sustainability and to produce some economic and social benefits of sustainability (Bibri and Krogstie 2020a; Joss 2010; Joss et al. 2013; Kenworthy 2006; Mostafavi and Doherty 2010; Rapoport and Vernay 2011; Suzuki et al. 2010). The change is still inspiring and the endeavor continues to induce scholars, practitioners, and policymakers alike to enhance the existing models of sustainable cities or to propose new integrated models to improve sustainability in today's world of advanced science and technology and intensive urban growth.

Transformative processes within sustainable cities have been in focus for some time now. The motivation for achieving the United Nations' Sustainable Development Goal (SGD) 11 has increased the need to understand, plan, and manage sustainable cities in new and innovative ways (United Nations 2015a). This is in response to the negative unintended consequences of urbanization. Nonetheless, this global trend creates enormous environmental, social, economic, and spatial changes, which provide an opportunity for sustainability with the potential to apply advanced technologies in order to use resources more efficiently and control them more safely, to promote more sustainable land use, and to preserve the biodiversity of natural ecosystems and reduce pressure on their services, with the ultimate aim to improve economic and societal outcomes. The United Nations's 2030 Agenda regards advanced Information and Communication Technology (ICT) as a means to promote socio–economic development and protect the environment, increase resource efficiency, achieve human progress and knowledge in societies, upgrade legacy infrastructure, and retrofit industries based on sustainable design principles (United Nations 2015b). This relates to the multifaceted potential of smart cities, which has been under study with respect to the role of big data technologies and their novel applications in strategic sustainable development within the framework of 2030 Agenda (United Nations 2015c). The abundance of data opens up for new opportunities for innovation in sustainable cities.

Big data technologies are heralding a new era wherein sustainable cities are morphing in response to the influence brought by the emerging paradigm of big data computing. Indeed, there has recently been a conscious push for sustainable cities across the globe to be smarter and thus more sustainable by adopting data-driven technologies to enhance and optimize their operations, functions, services, designs, strategies, and policies. This transformation—which entails new and innovative ways of how sustainable cities can be monitored, understood, analyzed, and thus planned, organized, controlled, and regulated—is manifest in the increasingly level of the development and implementation of data-driven solutions in their operational management mechanisms and development planning approaches. In fact, big data technologies have, in the context of sustainability, become as essential to the functioning of smart cities (e.g., Angelidou et al. 2017; Bibri 2019a; Bibri and Krogstie 2020b, c; Bettencourt 2014; Eden Strategy Institute 2018; Hashem et al. 2016; Kumar and Prakash 2016; Nikitin et al. 2016; Perera et al. 2017; Thakuriah et al. 2017) as to that of sustainable cities (e.g., Bibri 2020b, c; Bibri and Krogstie 2017, 2020a c; Pasichnyi et al. 2019; Shahrokni et al. 2014a, b; Shahrokni et al. 2015a, b; Sun and Du 2017; Thornbush and Golubchikov 2019). It is worth pointing out that while sustainable cities has had the leading position in tackling the challenges of sustainable development since the early 1990s, it was not until recently that smart cities gained momentum for facilitating the transition towards sustainable development thanks to the Internet of Things (IoT) and big data analytics. Regardless, urban processes and practices are becoming highly responsive to a form of data-driven urbanism. In other words, we are moving into an era where instrumentation, datafication, and computation are routinely pervading the very fabric of both sustainable cities and smart cities. One of the consequences of data-driven smart sustainable urbanism is that city systems and domains are becoming much more tightly interlinked, integrated, and coordinated. And also, vast troves of data are being generated, analyzed, harnessed, and exploited to make sustainable cities safer, cleaner, more resilience, and, above all, more efficient.

There are many opportunities yet to explore for integrating sustainable cities and smart cities in terms of their operational management and development planning in order to overcome or mitigate the extreme fragmentation of their landscapes and the weak connection of their strategies and solutions (e.g., Ahvenniemi et al. 2017; Angelidou et al. 2017; Bibri 2019b, 2020; Bifulco et al. 2016) under what is labelled "data–driven smart sustainable cities." Underlying this emeging paradigm of urbanism is the idea of combining the strengths of sustainable cities and smart cities and harnessing the synergies of their strategies and solutions in ways that first and foremost enhance, optimize, and maintain the performance of sustainable cities on the basis of the innovative data-driven technologies offered by smart cities. These strengths and synergies can be clearly demonstrated by combining the advantages of sustainable urbanism and smart urbanism. To enable such combination, major institutional transformations are required in terms of enhanced and new practices and competences.

As a process of change, data-driven smart sustainable cities as an emerging approach to sustainable urban development is where “the direction of investments, the orientation of technological development, and institutional changes are all in harmony and enhance both current and future potential to meet human needs and aspirations” (World Commission on Environment and Development (WCED) 1987). Drastic shifts to socio–technological regimes—transforming technological regimes for sustainable urban development—“entail concomitantly radical changes to the socio–technical landscape of politics, institutions, the economy, and social values” (Smith 2003, p. 131). Socio–technological regimes—i.e., “interconnected systems of artifacts, institutions, rules, and norms” (Berkhout etal. 2003, p. 3)—are to be brought about by the actions and networks of existing actors within civic institutions in the ambit of emerging data-driven smart sustainable cities. As stated by Bibri and Krogstie (2016, p. 33), “established socio–technological regimes can induce and support the transformation of socio–technical constellations (e.g., industry associations, research communities, policy networks, and advocacy/special–interest groups) towards improving and advancing sustainability at the macro level.”

Data-driven technologies and data-oriented institutions are benefiting from the provisioning of innovative applications and enhanced decision-making processes in response to the need for solving or mitigating the challenges of sustainability and urbanization. This in turn implies that they are displaying positive feedbacks through the increasing implementation of applied solutions and policy instruments, respectively, in sustainable cities and smart cities such that the more they are implemented, the more likely they are to be further implemented. Social processes behind this phenomenon commonly include network effects, interactive processes, adaptation, coordination, and learning.

This paper identifies, distills, and enumerates the key benefits, potentials, and opportunities of sustainable cities and smart cities with respect to the three dimensions of sustainability, as well as the key institutional transformations needed to support the balancing of these dimensions and to enable the introduction of data-driven technology and the adoption of applied data-driven solutions in city operational management and development planning.

This paper is based on the four case studies conducted as part of prior work on:

- compact cities (Bibri et al. 2020);
- eco-cities (Bibri and Krogstie 2020a);
- data-driven smart cities (Bibri and Krogstie 2020b); and
- environmentally data-driven smart sustainable cities (Bibri and Krogstie 2020c).

This is part of an extensive futures study, which aims to analyse, investigate, and develop a novel model for data-driven smart sustainable cities of the future. This takes the form of a strategic planning process of transformative change towards sustainability (Bibri and Krogstie 2021).

The futures study consists of 6 Steps in total, each with several guiding questions to answer. The answer to the guiding questions for each of these steps may involve one, two, or more papers, and one paper may in turn answer the guiding questions for one or two steps. This paper answers the last guiding question for both Step 5 and Step 6. Combining the answer to these two question in one paper is motivated by their interrelationship in regard to the three goals of sustainability, and the role of data-based city management in improving the contribution to these goals. The two guiding questions for Step 5 and Step 6 are as follows:

1. What are the key benefits, potentials, and opportunities of the future vision model of urbanism?
2. What institutional changes are necessary for attaining the future vision?

This paper unfolds as follows: Section 2 presents the methodological framework for the futures study. Section 3 presents the results. Section 5 discusses the results. This paper ends, in Section 5, with concluding remarks.

Research methodology

The methodological framework applied in the futures study combines and integrates normative backcasting and descriptive case study as qualitative approaches. The backcasting approach was employed to achieve the overall aim of the futures study. The case study approach, which is associated with the empirical phase of the futures study, was adopted to examine and compare two of a total of six cases from the ecologically and technologically leading cities in Europe with respect to each of the phenomena of compact cities, eco-cities, data–driven smart cities, and environmentally data-driven smart sustainable cities. Bibri (2020) dedicates a whole article to the methodological framework for strategic data-driven smart sustainable city planning whose core objective is clarifying which city model is desired and working towards that specified outcome. Table 1 presents the guiding questions for each of the six steps in the backcasting study, and highlights the two questions addressed by this paper in Step 5 and Step 6.

Backcasting as a strategic planning process

The term "backcasting," which was coined by Robinson in 1982, can denote a concept, a study, an approach, a methodology, a framework, or an interactive process among stakeholders. Hence, it has been defined in multiple ways. Robinson (1990, p. 823) defines backcasting as a normative approach that works "backwards from a particular desired end point to the present in order to determine the feasibility of that future and what policy measures would be required to reach that point." Once the future desired conditions are imagined and articulated, the necessary steps are defined and pursued to attain those conditions (Fig. 1). In recent years, backcasting has been mostly applied in the futures studies that deal with long-term problems and sustainability solutions (see, e.g., Akerman 2005; Akerman and Höjer 2006; Höjer et al. 2011; Miola 2008; Quist et al. 2001; Quist 2007; Vergragt and Quist 2011; Wangel 2011). However, the backcasting process in this futures study represents a strategic planning framework for facilitating progress towards achieving the goals of sustainability for those cities that are badging or regenerating themselves as sustainable, or manifestly planning to become

Table 1 The guiding questions for each step in the backcasting-oriented futures study

The guiding questions for the backcasting study
Step 1: Detail strategic problem orientation (Part 1)
1. What is the model of urbanism to be studied?
2. What are the aim, purpose, and objectives of the backcasting study in relation to this model?
3. What are the long–term targets declared by the goal–oriented backcasting approach?
4. What are the objectives these targets are translated to for backcasting analysis?
Step 2: Detail strategic problem orientation (Part 2)
1. What are the main prevailing trends and expected developments related to the model to be studied?
2. What are the key sustainability problems associated with the current model of urbanism and what are the causes?
3. How is the problem defined?
Step 3: Generate a sustainable future vision
1. What are the demands for the future vision?
2. How does the future model of urbanism look like?
3. How is the future model of urbanism different from the current model of urbanism?
4.What is the rationale for developing the future model of urbanism?
5. Which sustainability problems have been solved and which technologies have been used in the future vision?
Step 4: Conduct empirical research
1. What is the justification for the methodological framework to be adopted?
2. Which category of case study design is most relevant to investigating the dimensions of the future model of urbanism?
3. How many case studies are to be carried out and what kind of urban phenomena should they illuminate?
4. To what extent can this investigation generate new ideas and illustrate the theories applied and their effects, as well as underpin and increase the feasibility of the future vision?
Step 5: Specify and Integrate the components of the future model of urbanism
1. What urban and technological components are necessary for the future model of urbanism?
2. How can all these components be integrated into a framework for strategic sustainable urban development planning?
3. What are the key benefits, potentials, and opportunities of the future model of urbanism?
Step 6: Perform backwards–looking analysis
1. What built infrastructure changes are necessary for achieving the future vision?
2. What sustainable urban infrastructure changes are necessary?
3. What smart urban infrastructure changes are necessary?
4. What social infrastructure changes are necessary?
5. What technological infrastructure changes are necessary?
6. What institutional changes are necessary?

Source: Bibri 2020d, p.18)

smart sustainable in the era of big data. Accordingly, it articulates strategic thinking—the why—behind both the vision of the future and the plan for getting there.

Descriptive case study

The descriptive case study approach was applied in the four case studies to investigate the prevailing models of sustainable urbanism and the emerging models of smart urbanism (Step 4). The intention of this investigation is to specify the underlying

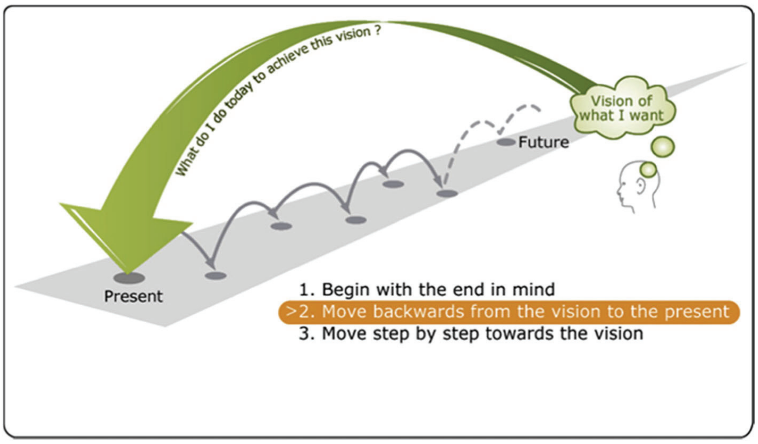

Fig. 1 The backcasting process from the Natural Step. Source: Holmberg (1998)

components of the future model of urbanism in terms of its core dimensions, strategies, and solutions, and then to integrate these components into an applied theoretical framework for strategic sustainable urban development planning (Step 5). This is in turn intended to inform and guide the strategic planning process of transformative change towards sustainability, which represents the novel model for data-driven smart sustainable cities of the future (Step 6). This paper relates to the institutional aspects of such process.

The case study is a descriptive qualitative methodology that is used as a tool to study specific characteristics of a complex phenomenon. The descriptive case study approach, as defined by Yin (2014, 2017), was identified as the most suitable methodology for the empirical phase of the futures study. This methodology has been chosen considering the nature of the problem being investigated, the research aim, and the present state of knowledge with respect to the topic of data-driven smart sustainable cities. In this context, it involves the description, analysis, and interpretation of the four urban phenomena in question in terms of their characteristics, with a particular focus on the prevailing conditions pertaining to plans, projects, and achievements. That is, how the selected cities behave as to what has been realized and the ongoing implementation of plans based on the corresponding practices and strategies for sustainable development and technological development. To obtain the knowledge sought to be gained, a five-step process tailored to each of the four case studies conducted was adopted (see Table 2):

The case studies examine contemporary real-world phenomena and seek to inform the theory and practice of data-driven smart sustainable urbanism by illustrating what has worked well, what needs to be improved, and how this can be done. They are particularly useful for understanding how different elements fit together and (co-)produce the observed impacts in a particular urban context based on a set of intertwined factors and actors.

Results

The focus of the results in this paper is on the institutional changes related to the novel model for data-driven smart sustainable cities of the future developed by Bibri and

Table 2 A five-step process tailored to the four case studies conducted

Compact Cities

- Using a narrative framework that focuses on the compact city model and its contribution to the three goals of sustainability as a real–world problem and that provides essential facts about it, including relevant background information
- Introducing the reader to key concepts, strategies, practices, and policies relevant to the problem under investigation
- Discussing benefits, conflicts, and contentions relevant to the problem under investigation
- Explaining the actual solutions in terms of plans, the processes of implementing them, and the expected outcomes.
- Offering an analysis and evaluation of the chosen solutions and related issues, including strengths, weaknesses, tradeoffs, and lessons learned.

Eco-Cities

- Using a narrative framework that focuses on the eco-city as a real-world problem and provides essential facts about it, including relevant background information
- Introducing the reader to key concepts, models, and design strategies relevant to the problem under investigation
- Discussing benefits and research gaps and issues relevant to the problem under investigation
- Explaining the actual solutions in terms of plans, the processes of implementing them, and the expected outcomes
- Offering an analysis and evaluation of the chosen solutions and related issues, including strengths, weaknesses, tradeoffs, and lessons learned.

Data-Driven Smart Cities

- Using a narrative framework that focuses on the data-driven smart city as a real–world problem and provides essential facts about it, including relevant background information
- Introducing the reader to key concepts, technologies, and data-driven smart sustainable urbanism processes and practices relevant to the problem under investigation
- Providing an overview of the literature review previously conducted in relation to the study, which delivers a comprehensive, state–of–the–art review on the sustainability and unsustainability of smart cities in relation to big data technology, analytics, and application in terms of the underlying foundations and assumptions, research problems and debates, opportunities and benefits, technological developments, emerging trends, future practices, and challenges and open issues
- Explaining the actual solutions in terms of plans, the processes of implementing them, and the expected outcomes
- Offering an analysis and evaluation of the chosen solutions and related issues, including strengths, weaknesses, tradeoffs, and lessons learned.

Environmentally Data-Driven Smart Sustainable Cities

- Using a narrative framework that focuses on data-driven smart solutions and their role and potential in improving and advancing environmental sustainability in the framework of the smart sustainable city as a real–world problem, and provides essential facts about it, including relevant background information.
- Introducing the reader to key concepts, core enabling technologies, infrastructures, landscapes, frameworks, as well as urban operating systems and urban operations centers, all with relevance to the problem under study.
- Identifying the commonalities and differences between the two cities with respect to the emerging technologies
- Explaining the actual solutions in terms of plans and visions, the processes of implementing them, and the realized and expected outcomes
- Offering an analysis and evaluation of the relevant solutions and related issues, including strengths, weaknesses, and lessons learned.

Bibri 2020d, p. 25)

Krogstie (2021) and the associated direct and indirect effects on the balancing and advancement of sustainability goals. Therefore, this paper is an integral part of the analytical side of the backcasting process, i.e., the specific step of looking back from the desired future to the present to determine the decisive steps on how to attain the future vision. Prior to this, Bibri and Krogstie (2021) identify a series of actions and measures pertaining to built infrastructure, sustainable urban infrastructure, smart urban infrastructure, social infrastructure, and technological infrastructure. These constitute the core dimensions of the landscape of the data-driven smart sustainable city of the future, and are associated with the transformations that are necessary for reaching the future vision. In order to bring about these transformations, a number of strategies and pathways were developed in the form of recommendations based on the case study research carried out on six of the ecologically and technologically leading cities on Europe. This paper as a final work of the backcasting study distills the core institutional practices and competences in terms of what has been enhanced, created, and established on the same basis in the form of actions, measures, and functions.

Benefits, potentials, and opportunities for environmental, social, and economic sustainability

One of the goals that is necessarily present in most backcasting studies is analyzing the benefits, potentials, and opportunities of the future vision. The desired vision of the future as constructed by Bibri and Krogstie (2020d), p. 89) is as follows:

> *"A form of human settlements that secures and upholds environmentally sound, economically viable, and socially beneficial development through the synergistic integration of the more established strategies of sustainable cities and the more innovative solutions of data-driven smart cities towards achieving the long-term goals of sustainability."*

At the core of the future vision is the idea of retaining the best of what we already have that have been successfully enacted in real-world cities, making use of the things that have been demonstrably better in the past, while being selective in adopting the best of what is emerging and promising, making use of the things that will add a whole new dimension to sustainability in terms of harnessing its synergic effects, balancing its dimensions, and thus boosting its benefits. This entails combining and integrating the prevailing models of sustainable urbanism and the emerging models of smart urbanism in terms of their strategies and solutions. The benefits, potentials, and opportunities that can be offered by each of these models are presented next.

Eco-cities

The eco–city has emerged, over the last four decades or so, as a response to the environmental challenges of sustainable development. Register (2002) defines an eco-city as "an urban environmental system in which input (of resources) and output (of waste) are minimized." According to Jabareen (2006, p. 47), it is an umbrella term that "encompasses a wide range of urban–ecological proposals that aim to achieve urban sustainability. These approaches propose a wide range of environmental, social, and institutional policies that are directed to managing urban spaces to achieve sustainability."

The eco-city focuses more on the environmental dimension of sustainability in terms of the natural environment and ecosystems than on the economic and social dimensions of sustainability (e.g., Mostafavi and Doherty 2010; Holmstedt et al. 2017;

Rapoport and Vernay 2011). There are many models of the eco–city according to an extensive literature review conducted by Bibri (2020b). These models can be caterogarized into three types: type 1 emphasizes passive solar design, type 2 combines passive solar design and greening, and type 3 focuses on green energy technologies and/or smart energy and environmental technologies (Table 3).

Accordingly, while the benefits of the eco-city are mostly of an environmental nature, they also include some economic benefits pertaining to green technologies (Table 4).

Compact cities

The compact city is the most advocated model of sustainable urban form due to its ability to deliver the expected benefits of environmental, economic, and social sustainability, yet to varying degrees. So, when strategically planned and well–designed, the compact city becomes able to support the balancing of the three dimensions of sustainability through such design strategies as compactness, density, multidimensional mixed-land use, sustainable transformation, and green open spaces (e.g., Bibri 2020c; Burton 2002; Dempsey 2010; Hofstad 2012; Jenks and Jones 2010; OECD 2012). Burton (2002) describes the compact city as "a relatively high–density, mixed–use city, based on an efficient public transport system and dimensions that encourage walking and cycling." Table 5 presents the key benefits of the compact city in relation to the three dimensions of sustainability.

Data-driven smart cities and environmentally data-driven smart sustainable cities

The data-driven city is an emerging paradigm of smart urbanism, and the environmentally data-driven city is an emerging paradigm of smart sustainable urbanism. The former tends to use advanced solutions to improve the different aspects of sustainability, attempting to cover environmental, economic, and social aspects of sustainability (Bibri and Krogstie 2020b; Nikitin et al. 2016; Noori et al. 2020). According to Nikitin et al. (2016), a data-driven city is characterized by the ability of city management agencies to use technologies for generating, processing, and analyzing data flows in order to develop and implement solutions for improving the living standards of citizens thanks to the development of social, economic and ecological areas of the urban environment. In other words, it is a digitally instrumented, datafied, and networked city that enables large-scale computation to extract useful knowledge for decision making purposes related to the different aspects of operational management and planning development in line with the goals of sustainability.

The latter is associated with the environmental dimension of data-driven smart sustainable cities. A data–driven smart sustainable city is a city that as increasingly

Table 3 Three types of the common eco-city models

Type 1	Type 2	Type 3
• Eco-village • Solar city • Solar village • Cohousing	• Eco–City • Eco–District • Environmental City • Green City • Garden City • Sustainable Neighborhood • Living Machines	• SymbioCity • Carbon Neutral City • Zero Energy City • Zero Carbon City • Low Carbon City • Ubiquitous Eco–City • Smart Eco–City • Data-Driven Smart Eco-City

Table 4 The key environmental and some economic benefits of the eco-city

Green infrastructure

• Providing ecosystem services:

  Air quality

  Recreation

  Climate mitigation and adaptation

  Flood risk mitigation by slowing and reducing stormwater discharges

  Temperature regulation

  Passive irrigation

  Biodiversity and habitat

  Stormwater management

• Managing water by mimicking the natural water cycle

• Improving the quality of water by protecting local waterways from stormwater pollutants

• Replacing or complementing technical systems

• Making urban areas more pleasant by improving their design aesthetics

• Improving economic attractiveness through greening, e.g., high land values which create a willingness to invest and develop urban areas

• Enhancing community safety and the quality of life

• Removing harmful substances from the air and thus increasing its quality

• Reducing stress as linked to mental and physical well-being and the development of illness.

• Providing favorable conditions for healthier life

• Reducing traffic noise and providing cooler temperatures and greater diversity

Sustainable energy systems

• Maximizing energy efficiency

• Conserving energy by combining heat and power provisions

• Reducing CO2 emissions due to the use of renewable energy sources:

  Wind, solar, and hydropower produce little or no air pollution

  Biomass and geothermal do emit air pollutants, but at much lower rates than most fossil fuels

• Enabling districts to become fossil fuel–free, zero-carbon, and climate positive

• Reducing energy costs and ecological impact to the lowest possible level

• Diversifying energy supply and reducing dependence on imported fuels

• Clean and cheap to run

• Mitigating large-scale failure due to a distributed, modular fashion deployment

• Distributing electricity with less complex and time-consuming infrastructural development thanks to the quick rollout of technologies in response to the needs of the city during critical events or complex emergencies

Sustainable waste management system

• Decreasing the landfilling of household waste and other waste

• Rising the recovery of material for reuse and recycling, as well as of energy in the form of heat and electricity

• Generating biogas fuels from food sludge and other organic waste as well as from wastewater and sewage

• Converting food waste into bio–fertilizer that can replace artificial fertilizers

• Mitigating Greenhouse Gases (GHG) emissions from waste incineration, irrespective of the quantity of the incinerated waste

• Reducing he environmental impact of waste management: GHG emissions and emissions of hazardous substances (e.g., organic pollutants, heavy metals)

• Reducing the noise and congestion caused by garbage collection trucks thanks to the bins connected directly to the underground repositories, where waste is sucked out by vacuum chutes via underground pipes

Sustainable materials

• Increasing productivity

Table 4 The key environmental and some economic benefits of the eco-city *(Continued)*

• Improving health and quality of life
• Decreasing waste generation
• Using materials in more effective ways
• Reducing air pollution
• Avoiding noise pollution
Green technology development
• Spurring green-tech innovations
• Increasing green-tech manufacturing and export
• Stimulating R&D projects and opportunities
• Inspiring entrepreneurship and creating startups
• Increasing industrial and technological investments
• Providing a significant number of jobs and opportunities for skill development
• Stimulating cooperation between government, industry, and academia
• Providing opportunities for international collaboration among urban actors

composed of and monitored by ICT of pervasive and ubiquitous computing and thus has the ability to use the IoT and big data technologies to generate, process, analyze, and harness urban data for the purpose of creating deeper insights that can be leveraged to make strategic decisions that accurately address the problems and issues related to sustainability and urbanization. A data–driven smart sustainable city is depicted as constellations of instruments across many scales that are connected through multiple networks characterized by high speed and intelligence, which provide continuous data regarding the different aspects of urbanity in terms of the flow of decisions about the environmental, economic, social, physical, and spatial forms of the city, supported by urban intelligence functions.

Furthermore, the two emerging models of urbanism are evolving into real-time functioning cities based on the data routinely collected from the sensors deployed across urban environments, which can provide useful information about longer term changes (see, e.g. Ameer and Shah 2018, Batty et al. 2012; Kitchin 2014; Nikitin et al. 2016; Shahrokni et al. 2014a, b; Rathore et al. 2016, Sinaeepourfard et al. 2016). As such, they involve not only benefits, but also potentials and opportunities that are yet to be exploited and explored respectively (Table 6).

Institutional transformations: practices and competences

To boost the effects of sustainability through combining the benefits, potentials, and opportunities of the prevailing models of sustainable urbanism and the emerging models of smart urbanism requires major institutional transformations and socio-technical transitions. There is a growing perception that the centripetal movement of data-driven smart sustainable interests, ideas, and considerations in urban strategies, technological innovations, and institutional developments can have a significant impact on data-driven smart sustainable–induced processes of transformation in the core practices, primary operations, and central institutions of modern society. This is what the data-driven smart sustainable city of the future entails as a strategic roadmap to transformational change. This process is designed to create major changes in the processes

Table 5 The contribution of the compact city to the three goals of sustainability

Environmental sustainability

- Lowering per capita rates of energy use and CO2 emissions through district-wide energy utilization and local energy generation
- Conserving energy by combining heat and power provisions made possible by population densities
- Lowering energy consumption and reducing pollution due to the proximity to workplaces, services, facilities, and public spaces
- Reducing car dependency and thus CO2 emissions through promoting a walking and cycling environment
- Decreasing travel needs and costs and shortening commute times
- Minimizing the transportation of energy, materials, water, and products, thereby reducing CO2 emissions due to the compactness of the built form
- Optimizing the efficiency of public transport by promoting transit-oriented development in built-up areas
- Limiting the consumption of building and infrastructure materials
- Reducing the pressure on ecosystem services and biodiversity provided by green and natural areas
- Limiting the loss of green and natural areas
- Protecting rural and agricultural land from further development through the optimum use of land resources

Economic sustainability

- Supporting local services and businesses through population densities by providing a larger customer basis for commercial activities
- Revitalizing city centers through the promotion of densely built dwellings, shops, businesses, and accessible infrastructure and facilities
- Extending and enhancing public transportation infrastructure and facilities
- Creating proximity between workers and their workplaces, which results in higher productivity due to shorter travel time for workers
- Greater diversity of employers and thus job possibilities
- Increasing the likelihood of workers finding jobs that match their skills, which also results in higher productivity
- Greater productivity due to more diversity, vitality, innovation, and creativity
- Attracting skilled labor force by high quality of life due to better access to a diversity of local services and jobs
- Maintaining the diversity for choice among workplaces, service facilities, and social contacts
- Requiring less and cheaper per capita infrastructure provision due to more efficient public service delivery

Social sustainability

- Creating a better quality of life through more social interaction, community spirit, and cultural vitality due to the access by proximity to facilities, workplaces, public spaces, public transportation, as well as the opportunity for walking and cycling
- Reducing crime and providing a feeling of safety through natural surveillance
- Improving social equity through better access to services and facilities and flexible design of housing in terms of mixed forms and affordability
- Maintaining public service level for social welfare by improved efficiency
- Greater accessibility due to lower cost enabled by shorter intra-urban distances
- Lowering transport costs, higher mobility for people without access to a car, and improved human health due to more cycling and walking
- Enhancing social cohesion through a sense of belonging and connectedness
- Supporting human, psychological, and physical health through ready access to open green space, walkability in neighborhoods, and social contact
- Enhancing livability in terms of social stability and cultural and recreational possibilities
- Healing spatial segregation by forging the physical links and bridging barriers between communities

Table 6 The key benefits, potentials, and opportunities of the data-driven smart city and the environmentally data-driven smart sustainable city

Transport and traffic management

- Reducing energy usage and harmful emissions
- Providing the opportunity to alter demand for carbon-intensive vehicles using disincentives
- Increasing and maintaining safety for vehicle drivers by detecting accidents and responding timely to critical events through alerts
- Predicting traffic conditions for decreasing congestion by directing vehicles to alternative roads
- Reducing noise pollution through smart traffic lights and smart parking
- Improving the security and reliability of the overall transport system
- Encouraging and attracting people to cycle thanks to dynamic signage system, thereby reducing CO2 emissions resulting otherwise from more polluting forms of energy-intensive transport
- Enhancing mobility for citizens and thus increasing the level of their life satisfaction
- Providing the opportunity for contactless payment and thus minimizing environmental impacts
- Providing the opportunity for obtaining more detailed information on transport and mobility thanks to the unified public transport system
- Tracking traffic occupancy for planning public transport routes in a more flexible way
- Identifying the user priorities of public transport areas and developing new routes in response to new demands
- Improving, re–engineering, or developing transport infrastructure based on historical mobility and congestion data
- Decreasing the need for parking spaces on the streets through car sharing system
- Supporting equity and inclusion through socially sustainable public transport thanks to smart mobility apps
- Providing information to passengers about traffic occupancy/irregularities of public transport, which allows them to plan their way more efficiently

Smart power grid

- Improving the transmission efficiency of electricity
- Optimizing distribution networks in terms of energy demand/supply
- Restoring after and reacting timely to potential disturbances in power supply
- Reducing operation, maintenance, and management costs
- Integrating different systems of renewable energy
- Reducing electricity bills and thus saving money as well as balancing the electricity system through efficient electricity networks
- Making storage decisions based on the monitoring of power generation and power demands
- Helping governments to react promptly to emergencies, critical events, or natural disasters, e.g., severe storms, earthquakes, and large solar flares, through adding resiliency to large-scale power systems
- Curbing energy usage, conserving energy, reducing costs, and maximizing the transparency and reliability of the energy supply chain
- Avoiding potential power outages resulting from high demand on energy using dynamic pricing models for power usage by increasing charges during peak times to smooth out peaks and applying lower charges during normal times.
- Avoiding carbon–intensive peaks using new ways of coordination with regard to the overall ensemble of users and consumers.
- Supporting decision–making pertaining to the generation and supply of power in line with the actual demand of users and consumers
- Improving coordination and planning around power generation from renewable plants depending on wind or sun.
- Monitoring and analyzing energy consumption in real time across multiple spatial scales and over different temporal scales

Smart buildings

- Providing the potential for energy efficiency and GHG emissions reductions through such functions as:
  - Highly advanced automatic systems for efficient and natural lighting

Table 6 The key benefits, potentials, and opportunities of the data-driven smart city and the environmentally data-driven smart sustainable city *(Continued)*

- Temperature control
- Window and door operation
- Smart appliances
• Keeping the building's climate within a specified range
• Reducing energy consumption and energy costs
• Guaranteeing safety and security
• Providing the potential for decreasing heat demand and consequent GHG emissions by means of retrofitting residential buildings
• Assessing energy demand from large-scale retrofitting and exploring its impact on the supply side, thereby enabling more precisely targeted and better coordinated energy efficiency programs
Smart meters and energy monitors
• Allowing consumers to manage their energy usage based on what they actually need and afford by having access to live energy prices and adjusting their usage accordingly
• Enabling consumers to remotely control their home appliances and devices by means of such advanced functions as scheduling, programming, as well as reacting to contextual situations
• Allowing for self–optimization and self–control of energy consumption through integrating sensing and actuation systems in different kinds of appliances and devices for balancing power generation and usage
• Providing insights into how the energy flows can be influenced by the consumer behavior thanks to the in-house sensors that can report data on energy-using appliances
• Balancing electric loads and reducing power outages
• Allowing for dynamic pricing which lowers or raises the cost of electricity based on the current demand
• Providing homeowners with convenience and cost savings
• Offering homeowners sophisticated level of preprogrammed preferences in terms of turning on some appliances based on the amount of the energy consumed within a day, week, or month
Smart environmental monitoring
• Reducing the time needed for waste collection as well as the operating time of disposal machines
• Curbing fuel consumption and costs
• Reducing the number of waste disposal vehicles and containers and related service costs
• Reducing the level of harmful emissions through route optimization
• Decreasing noise pollution generated by waste disposal vehicles
• Providing health benefits and decreasing health risks through preventing the accumulation of waste
• Using historical and movement data
• Using historical data on disposed waste (places and volumes) for installing new waste containers
• Distributing the resources and logistics more efficiency, thereby significantly reducing the operational and infrastructural costs of waste collection system
Smart management of waste collection
• Developing a variety of preventive systems and measures for environmental quality and implementing them in a timely manner
• Enabling public authorities to observe the condition of the air and to forecast about its pollution
• Enabling government and non-governmental bodies to take decisions based on a more informed understanding of the quality of the environment
• Complementing energy efficiency solutions with respect to GHG emissions reductions
• Informing citizens and other city stakeholders about GHG emissions
• Ensuring companies' compliance with environmental regulations and evaluating the efficiency of the newly installed systems as well as the health of employees
• Evaluating the performance of environmental regulations and enforcements, whether they are working as anticipated, so that the government can take action to change the regulatory framework
• Stimulating research opportunities on the effects of certain pollutants on human, wildlife, or aquatic life so to create treatment procedures

Table 6 The key benefits, potentials, and opportunities of the data-driven smart city and the environmentally data-driven smart sustainable city *(Continued)*

- Finding risks to human and wildlife, scoping to population migration from high-density areas to low density areas, and restricting GHG emissions
- Identifying environmental stress, understanding environmental patterns, and assessing the effectiveness of strategies and programs
- Collecting critical information to make better policy decisions to reduce GHG emissions, as well as to guide citizens on making their own efforts in this regard
- Allowing the interpretation of the ambient air data based on the spatial and temporal representativeness of the data gathered and on the health risks involved in the exposure to the monitored levels
- Allowing the comparison of the different districts of the city in terms of various air pollutants
- Publishing hourly more detailed information for each pollutant in absolute value, and designing daily values for drawing a more complete picture at monitoring the level of pollution in the city
- Allowing users to explore the available information at maximum level due to the opportunity to gather information about the status of the atmosphere
- Allowing companies and enterprises in the industry to get an idea about the air quality, which makes it possible to make decision on the implementation of preventive measures for reducing pollution. This leads to the maximisation of their productivity in the long-term
- Allowing industries to access the air pollution forecasts, which simplifies the decision-making process in the manufacturing environment
- Predicting trends of the presence of air pollutants in the atmosphere
- Coping with the environment and lowering air and noise pollution levels to enhance the quality of life

Smart street lighting

- Facilitating many innovative applications related to traffic, mobility, air and noise pollution, parking, safety, and public Wi-Fi connectivity, just to name a few
- Enhancing the environmental performance and energy efficiency of the essential infrastructure of the city
- Optimizing the efficiency of the public-lighting installations in terms of operational and maintenance costs
- Reducing collision and the risk of collisions with cyclists and other vulnerable road users

Smart urban metabolism

- Providing holistic analysis of energy and material pathways to conceive of management systems and technologies that allow for the reintegration of natural processes, increasing the efficiency of resource use, and the conservation and production of energy
- Providing long–term opportunities in terms of enabling a new understanding of the causalities that govern urbanism
- Allowing citizens and city officials and stakeholders to receive real-time feedback on the consequences of their choices in a systematic way
- Understanding the GHG emissions resulting from the consumption of electricity, heat, water, and the production of waste
- Allowing the follow-up and evaluation of the evolution of urban metabolism, and facilitating the identification of the cause-and-effect relationships of the metabolic flows
- Providing rich datasets on energy and material flows at the city level in terms of both production- and consumption-based approaches

Smart management of urban infrastructure

- Improving incident management
- Enhancing emergency response coordination
- Mitigating risks and responding timely to critical events or unfavourable conditions
- Enhancing safety and service quality
- Reducing operational and maintenance costs
- Improving resources and logistics efficiency
- Reducing negative impacts on the environment
- Identifying, predicting, and responding to longer-term urban infrastructure needs

Table 6 The key benefits, potentials, and opportunities of the data-driven smart city and the environmentally data-driven smart sustainable city *(Continued)*

Smart citizens: participation and consultation

- Empowering citizens for community engagement and co-creation
- Improving the level of satisfaction and increasing the level of confidence and trust among citizens in the city administration
- Promoting widespread participation through new technologies that are essentially network-based and enable extensive interactions across many urban domains as well as spatial scales
- Enhancing equity and fairness and attaining a better quality of city life through new technologies that offer the prospect of ending the digital divides
- Enabling the citizenry to blend their personal knowledge with the knowledge of technology experts
- Informing political participation at all levels
- Engaging the citizenry in city planning, development, and governance
- Making it easier for citizens to find out about planning issues and improving the efficiency and effectiveness of local planning
- Enabling the planning service to perform better with fewer resources for property developers, architects, surveyors, and planning consultants
- Improving the transparency of the city management
- Providing the opportunity to track the quality of work of the management companies and contractors engaged in the provision of urban amenities and services, and to perform corrective actions in the work of local authorities
- Enabling citizens to participate in the technology and policy of the city through various platforms, such as classrooms for leaning, spaces for innovation, co-innovation centers, and participatory and democracy platforms
- Providing services by public agencies remotely and mobile kiosks, such as receiving certificates, publishing complaints, and obtaining necessary information. This improves the convenience of public services
- Determining trends in public opinion to be considered when forming urban development programs and initiatives

Smart public safety

- Empowering decision-makers to prepare for, respond to, and recover from natural disasters
- Increasing safety by identifying risks, threats, and vulnerabilities and providing early warnings
- Preventing adverse effects on public health by notifying citizens to evacuate or avoid certain urban areas
- Enhancing risk assessment and hazard identification to provide immediate responses
- Improving security by allowing or denying access to certain individuals to public places, as well as preventing potential unrest
- Providing the opportunity for increasing urban resilience
- Informing the responsible public and private actors of transportation–related safety and health issues to make improvements

Smart healthcare

- Electronization of medical services:
  - Making medical services more accessible to the public
  - Accelerating the process of customer services
  - Allowing more flexible arrangement of visits to doctors and obtaining the right specialist
  - Enabling physicians to get rid of paper routine and to always have access to data about patients, the history of their diseases, and the medicines they take
  - Providing the municipal administration with reliable and efficient tools for analysis of medical institutions activities
  - Providing the administration with the opportunity of managing resources more efficiently
  - Enabling transparent reporting and planning for future purchases and saving costs for the city budget.
- Large-scale electronization system:
  - Improving the comfort of using public medical services
  - Optimizing the availability and workload of physicians in medical institutions

Table 6 The key benefits, potentials, and opportunities of the data-driven smart city and the environmentally data-driven smart sustainable city *(Continued)*

- Enabling managing flows of patients and outpatient integrated medical records
- Keeping consolidated management records and personalised accounts of medical assistance
- Making online and rescheduling appointments
- Checking-in without preliminary cancellation and obtaining medical certificates online
- Finding the nearest clinic nearby place of residence
- Gathering information about the workload of medical institutions and the demand for doctors
- Managing medical registers and solving medical and organisational tasks relating to different categories of citizens, those with certain diseases.
• Enhancing diagnosis and treatment processes and tailoring care services
• Providing precautionary and proactive care services
• Prolonging human life and promoting human well-being
• Enabling remote services such as diagnosis and telemedicine
• Improving the quality of recommendations and reducing the time spent on making them as well as on diagnostics
• Providing accurate, appropriate, and history-aware responses to health problems
• Flagging potential health issues frequently or on a demand basis by monitoring, processing, and analyzing complex occurrences
• Predicting and responding to disease outbreaks, critical events, and new trends

of sustainable cities and the behaviors of their actors, as well as to produce significant improvements in their performance. The focus in this paper is on the institutional aspects of this process, which affect revolutionary change within modern cities. Generally, institutional transformation denotes profound changes within institutions in the basic values, and beliefs that are dominant, as well as in the rules and regulations that lead to certain outcomes. In other words, at its deepest level, it refers to changes in the ideas, interests, and considerations that govern institutions, which in turn lead to changes in practices and related apparatuses. Institutional transformation explains the change of institutions that govern human interactions and paths of development in society. Institutions are defined as “actions, rules, social structures and practices that persist over time and are features of social aggregate that are larger than a single organization” (Murmann 2003).

It is within the remit of institutions to facilitate the implementation of data-driven technology solutions in city operational management and development planning to improve and advance sustainability through regulatory frameworks and social norms. There is a strong institutional support and commitment to big data technology—industry associations and consortia, business communities, research communities, policy networks, regulatory and legal bodies, and governmental agencies—within sustainable urbanism and smart urbanism given its untapped potential, rapid expansion, and wide success as to advancing scholarly research and enhancing social practice (see Bibri 2019c for a detailed discussion).

Supporting the balancing of the three dimensions of sustainability

Sustainable cities are in a constant state of unprecedented transformative changes in response to emergent internal and external factors, such as climate change, urbanization, technological shifts, economic crises, pandemics, and demographic changes. Managing sustainable cities is a very complex function that encompasses strategies, approaches, activities, and instruments that make them work. This means that:

- Their infrastructures are accessible and functional
- Their energy systems are sustainable and efficient
- The needed natural resources and public services are available and equitably distributed among citizens
- Their designs are efficient and scalable
- Their plans are comprehensive, dynamic, and continuous
- The interests of the different stakeholders, especially citizens, are well represented and count in decision making processes and in future developments
- Their economy is sustainable and prosperous.

All these aspects of sustainable development need to be planned and managed at a city administration level, but with a wider context in mind. It is important for a city government in collaboration with development agencies to make progress in developing flexible and action-oriented strategies. These should emphasize the interconnectivity of sectors and integrate a wide range of players while relying on advanced ICT as essentially network-based and an enabler of an extensive interaction across many sectors, supported by institutional structures and governance models.

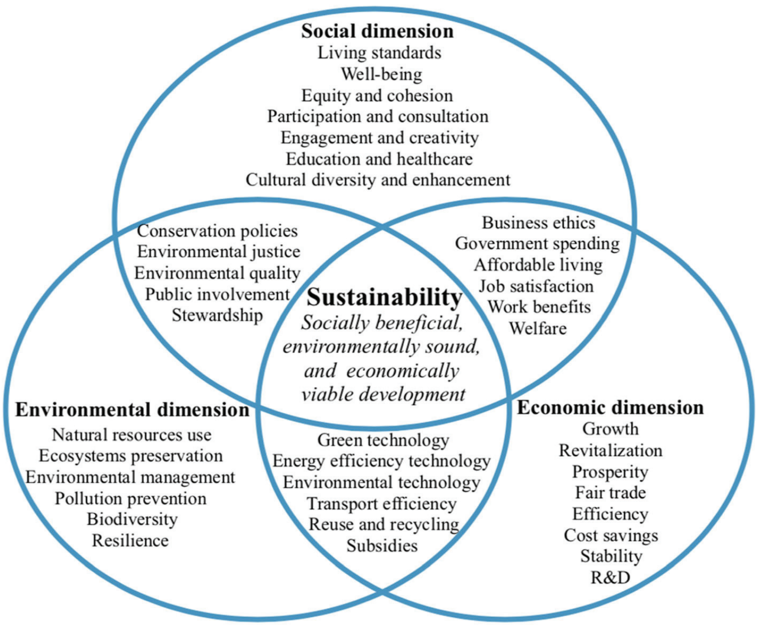

Fig. 2 A framework for balancing the three dimensions of sustainability

It is crucially important to ensure that the institutional practices and competences in the data-driven smart sustainable city of the future support the balancing of the environmental, economic, and social goals of sustainability (Fig. 2). This implies that concrete and distinct actions and measures should be in place as part of a coordinated framework to make the most of the opportunities offered by sustainable development and supported by technological development. The core institutional practices and competences needed in this regard are presented in Table 7 in the form of actions and measures, organized in accordance with the three dimensions of sustainability.

Introducing modern technology and adopting applied solutions in the city management

All traditional mechanisms of the city management (administration, organization, and planning) are gradually replaced with digital mechanisms enabling and supporting data-driven decision making. Big data analytics improves the quality and speed of decision making. Data-based city management relies on urban computing and intelligence for implementing the data-driven technology solutions developed for the various spheres of the city administration, including:

- Transport management
- Traffic management
- Street lighting management
- Mobility management
- Waste management
- Energy management
- Environmental monitoring
- Building management
- Public safety
- Healthcare and education

Urban computing and intelligence bridges the gap of ubiquitous sensing, intelligent computing, cooperative communication, and large-scale data processing and management technologies to create novel solutions to enhance urban forms, urban infrastructures, urban environments, and urban services. Such solutions can be developed through cloud and fog computing or city own facilities, the IoT devices, intelligent networks, artificial intelligence, and big data analytics.

In addition, data-based city management involves a number of agencies that use technologies for generating, processing, and analyzing data to adopt solutions for improving sustainability, efficiency, resilience, equity, and the quality of life for citizens. As such, it builds on the concept of the smart city: an urban area that uses different types of technologies to collect and analyze data to gain deep insights that can be applied to manage assets, resources, and services efficiently, thereby optimizing and enhancing urban operations and functions. However, in the current climate of intensive urban growth, the quality of the urban environment plays an increasingly key role in improving wellbeing. Data-based city management is a basic driver for the transformation of urban services and innovations, and will dramatically change the principles of managing the urban environment. It entails the

Table 7 The core institutional practices for supporting the balancing of the three dimensions of sustainability

Sustainability	Institutional Practices and Competences
Environmental Dimension	• Make green structure plans that map the city's green resources by assessing their natural and recreational qualities
	• Use green structure plans as a means to enhance and integrate the available knowledge of the green structure and create the opportunity to gain a coherent view of its totality, as well as to focus attention on the city's merits and shortcomings in regard to green structure preservation
	• Introduce balancing principles to compensate for any potential loss of natural and agricultural land with a new or reinforced land (e.g., recreational land), so the final result is more valuable
	• Establish a research center for environmental sustainability
	• Establish an innovation center for green energy technology
	• Transform the innovation center into an international meeting place where the city, the business community, and the research community work collaboratively to profile and demonstrate know–how in green energy technology
	• Establish a research and innovation center for zero emission neighbourhoods
	• Establish a living lab for zero-emission/net-zero energy buildings as a multipurpose experimental facility to study various technologies and design strategies in a real-world living environment
	• Establish a research and innovation center for green, passive, and low energy buildings
	• Support green energy technology innovation projects through funding schemes, advocating the adoption of environmentally friendly products and services, organizing symposiums on environmental innovations, encouraging local environmental programs, and devising comprehensive environmental plans
	• Create arenas where industry experts, businesses, politicians, and citizens meet to discuss environmental problems and potential solutions
Economic Dimension	• Promote regional collaboration to enhance business development
	• Make detailed regular plans for business development where the economic goals of sustainability are coupled with the targeted measures. This relates to the balanced scorecard**,** a strategic management performance metric used to measure and provide feedback to organizations by identifying and improving various internal business functions and their external outcomes
	• Make strategic business development plans to guide business and tourism development
	• Expand the tourism industry and boost the regional business links
	• Use physical planning to adapt the prioritized areas for development to business development
	• Create arenas where politicians, business actors, and public servants meet to discuss topical questions and issues
	• Support collaboration and networking with business actors to enhance knowledge and information sharing
	• Develop higher educational programs that integrate education and research into business development
	• Intensify collaboration between businesses, educational institutions, and research centers
	• Inspire and stimulate local entrepreneurship by providing financial support and counselling and by organizing contests between, and offering awards to, young entrepreneurs and innovators
	• Create various resources to support small and medium-sized enterprises
	• Establish a research center for innovation, entrepreneurship, and learning
	• Create R&D projects in light of new city development projects in the medium and long term based on partnerships between government, academia, and industry
	• Transform new successful sustainable urban development projects into sites that attract new investments, ventures, study visits, further development initiatives, and international interests
	• Ensure collaboration on and alignment with a shared vision of sustainability among companies, organizations, and institutions with different interests and goals
Social Dimension	• Make public health plans
	• Develop procedures that secure a linkage between urban planning and public health goals

Table 7 The core institutional practices for supporting the balancing of the three dimensions of sustainability *(Continued)*

	through initiatives to provide access to green and recreational areas, as well as arrangements to improve cycling and walking, thereby enhancing the opportunity to engage people in physical activity • Ensure that the social sustainability plan plays a prominent role in local policy-making, and constitutes the basis for political debate where solutions to the challenges and issues addressed are sought • Ensure that plans rest on statistics, indicators, and qualitative data as the basis of knowledge for political decisions • Make plans on the basis of the areas for improvement identified, and discuss and monitor them on an annual basis. The monitoring to be employed should include a number of issues, such as the number of newly built dwellings, the assortment of dwellings, the affordability of housing, the safety of public spaces, the ability to enhance the quality of life in the city's socio-economically weak and vulnerable areas, the ability to improve the air quality and reduce the noise level, the protection of green and natural areas, and so on • Develop strategic guidelines for social justice, social inclusion, social cohesion, and social capital so that they can be converted into concrete projects and programs • Establish a research and innovation center for social sustainability • Establish a research and innovation center for the IoT and people to study how the citizenry can get the most out of the IoT as a socially disruptive technology with respect to transportation, accessibility, energy, home automation, living, health, learning, and so on in terms of services • Establish a research center for ICT for sustainability aiming to contribute to changes in social institutions, social behaviors, social relations, and social perceptions in a sustainable direction • Establish a research center for sustainable development to contribute to the development of a sustainable society. This contribution includes the shift towards sustainable technical and social systems that meet human needs, such as food, housing, transportation, communication, and recreation • Create a participatory democracy platform that allows citizens to see and discuss proposals put forward by the city government, and submit their own. Such platform is used to create the city's government agenda, with proposals coming directly from the participating citizens • Create a city council that allows the provision of services by public agencies remotely and mobile kiosks, where one can receive various certificates, publish a complaint, get necessary information, and so on. This is to improve the convenience of public services received by citizens • Support and strengthen the technologies that ensure widespread citizen participation by security measures and privacy mechanisms. These should be at the core of the city policy and governance practices associated with the design, development, and implementation of interactive platforms. • Develop and implement advanced technologies that offer the prospect of ending the digital divide, provided that they do not open up other kinds of divides. It is important to explore how new forms of regulation at the level of urban planning, transport planning, economic development, and community development can be improved using future and emerging technologies • Establish a number of digital literacy programs and investigate the reasons behind the digital exclusion of minorities and vulnerable groups, with the overall aim of having everyone online, or with the aspiration to be online by 2050. • Develop and implement a unified medical information and analytical system, combining such services as communication center, electronic registry, electronic health record, electronic prescription, disability certificates, laboratory services, and personalized accounts. • Establish center for social innovation and entrepreneurship to create knowledge and ideas for environmental and social change that will be of relevance to the challenges that the city faces through research, education, and experiential learning. This is important to strengthen the capacity of individuals and organizations to develop innovative solutions to complex problems.

utilization of advanced services and development projects through new technologies to benefit people immensely in different ways and to make cities liveable and attractive, which leads to further developments. It brings cohesion and congruence to urban strategies and unifies the expectations of different urban actors in a way that the plans are feasible and adequate to the daily reality of a place, and that facilitates a shared vision of sustainable development.

The technical and institutional competences pertaining to the data-driven smart sustainable city of the future reflect the degree of its readiness to introduce data-driven technology in its management as well as the degree of the implementation of applied data-driven solutions in its management. The degree of readiness is characterized by the availability and development level of the technological infrastructure and competencies needed to generate, transmit, analyze, and visualize data. The degree of implementation demonstrates the extensive use of the applied technology solutions developed for operational management and development planning in relation to the different areas of sustainability. The competences are briefly described next along with their key functions.

Horizontal information platforms Both the data infrastructure and operating system for the city constitute what is called horizontal information platforms, a key competence for performing the core functions of big data analytics. Functionally compatible horizontal information platforms allow the creation of a united ecosystem for the city. They explicitly link together multiple urban technologies and solutions to enable greater coordination of the city systems and domains (Table 8):

Operations centers and dashboards The city systems and infrastructures will become much more tightly integrated and interconnected as manifested in what is called operations centers and dashboards. These draw together and interlink the data generated by the city complex to provide an integrated view and synoptic intelligence of the city (Table 9). The new digital technologies embedded and networked in urban environments will transfer the collected data to a number of control and management systems that can respond in real time to data flows.

Strategic planning and policy office The strategic planning and policy office as an analytical center is key to the management of the city development projects and

Table 8 The key functions of horizontal information systems

• Providing open platforms connecting all the sensors installed in the city and the obtained sensed data Aggregating and standardizing the flows of functional and territorial data from municipal sources, the systems of state control (mobility, energy, noise level, pollution level, etc.), business environment, and other state agencies (hospitals, cultural institutions, universities, schools, etc.), as well as from various detectors and cameras for their subsequent integrated analysis and visualization in 3D format
• Solving the problems of data disconnection in the city through the open operating system integrating and processing the information generated by the city
• Reworking and repackaging the collected data for daily consumption by different stakeholders
• Allowing the city authorities and third party users to gain access to the received data in a more structured and convenient manner for software development
• Providing comprehensive solutions to complex urban problems by integrating the self-contained and unconnected technological solutions and information systems used in the different functional departments of the city
• Improving the efficiency and performance of implemented applied technological solutions
• Allowing the city authorities and other users to take decisions on the optimization of the city activities in the short, medium, and long term

Table 9 The key functions of operations centers and dashboards

• Using visualization sites to help both expert and no-expert users interpret and analyze information, and to allow citizens to monitor the city for themselves and for their own ends
• Employing integrated, real-time data to track the performance of the city and to communicate the live feeds of real-time information to citizens with respect to a number of areas
• Enabling automated systems to respond to citywide events by making immediate decisions pertaining to various urban domains
• Overcoming urban challenges, keeping citizens up-to-date, and developing applications based on the standardized and published forms of open data
• Creating innovative platforms, promoting big data use and application, introducing data-driven technologies, and providing expert assistance

programs pertaining to the implementation and integration of the compact, ecological, and technological aspects of the landscape of the city, particularly in relation the objectives and targets of sustainable development (Table 10).

Innovation and research centers The main function of innovation and research centers is to develop, test, and implement new solutions for the different areas of sustainability. Accordingly, they involve building, sharing, and continuously enhancing practical knowledge in response to the goals, strategies, policies, and visions of the city (Table 11).

Table 10 The key functions of strategic planning and policy office

• Promoting smart approaches through planning systems—making extensive use of data to guide urban planning and design and to encourage developers to deploy digital infrastructure to future proof new developments
• Analyzing population displacement and movement data for the strategic planning of city infrastructures, districts, and streets, thereby taking into account the emerging demands from the population
• Integrating information on the expectations/uses of the residents of the city districts in the construction of scenarios in response to the need for renewal, redevelopment, and development projects
• Developing master and comprehensive plans based on the analysis of the city data
• Integrating technology solutions and urban design solutions when developing urban plans and urban development projects
• Using a one-stop data analytic hub to bring and weave together data from a variety of city agencies and departments in order to regulate and govern the city and to solve related issues
• Collating and analyzing data from a variety of city agencies and departments to enable the city authorities to make decisions more effectively in the fight against crime and on the provision of public safety and quality of life of the city residents
• Prioritizing, based on data analysis, the development of the municipal system and ways to improve the efficiency and effectiveness in the provision of urban services, enforcement of laws, as well as the transparency of the city authorities. Among the primary directions of the initiatives to deal with in this regard are:
- Support of the city's functions by communication with other city agencies, e.g., adoption of resolutions in the form of models based on data analysis
- Data transfer by establishing a platform for exchange of data among various departments, combining data from different sources of various agencies and third party organisations. This can occur through cooperating with the ICT department and the operations centers of the city
- Creation of open data portal to be available to anyone interested
• Developing and implementing strategies for technological development in the city
• Addressing issues of city-wide coordination and cooperation in the field of technologies, playing a bridging role, and advising various city agencies and departments on technological innovations

Table 11 The key functions of innovation and research centers

• Creating multidisciplinary teams based on practical know how, long–standing experience, international expertise, and access to global networks
• Enabling interaction and promoting cooperation between scholars, researchers, industry experts, business professionals, and thought leaders to enhance research opportunities, academic excellence, real-world problem solving, and knowledge creation and dissemination
• Providing the ground for developing and testing innovative technological solutions for urban management
• Featuring the latest developments in technologies and solutions and demonstrating how they are applied in real-world settings
• Developing urban intelligence functions for improving and optimizing city operations, functions, services. Designs, and strategies
• Understanding, enhancing, and applying the leading city practices
• Integrating resources and expertise for the benefits of the city through collective intelligence
• Managing, analyzing and visualizing different kinds of projects
• Supporting the city authorities in visioning, strategizing, and implementing sustainable development as a set of objectives and targets

Educational centers and training programs The educational centers and training programs are associated with the creation and accumulation of knowledge and expertise in the areas of urban science, urban informatics, data science, computer science, data-intensive science, and big data analytics and their integration into interdisciplinary fields in relevance to sustainable urban development (Table 12). These disciplines are heavily applied fields where the programs offered by the educational institutions should be adequate for enabling the data scientists, experts, and analysts to perform their tasks. The intention is to provide the city with the competences needed to successfully implement the applied technology solutions to improve and advance sustainability.

Competence centers It is important to establish various competence centers as multidisciplinary and multi-stakeholder research and demonstration arena. These centers should address newer subject areas, where efforts should often be conducted in joint projects with businesses and various societal bodies. As autonomous units, they should maintain close connections with industry and act as liaison offices between the hosting universities in the city and other universities in the country. Competence centers should be created in cooperation with all stakeholders of the quadruple helix at the national level, a solution that needs generous support from the government as well as expertise within the various areas of sustainability and technology. Among the

Table 12 The key functions of educational centers and training programs

• Developing educational programs at the intersection of big data analytics, sustainable development, and urban planning and development
• Providing specialized academic programs within urban analytics, urban computing, urban intelligence, and data-driven sustainable urbanism
• Offering a large number of educational programs with data science and analytics discipline
• Introducing data-driven technologies for city operational management and city development planning
• Implementing initiatives for developing competencies in a number of data science and analytics areas in relation to urban sustainability by conducting seminars and providing trainings to improve the level of the applied technological knowledge in this regard

Table 13 Competence centers for sustainability

• Center for sustainable built environment
• Center for construction efficiency and sustainability
• Center for traffic management research
• Center for transport management research
• Center for integrated sustainable transportation
• Center for smart grid and energy storage
• Center for integrated renewable solutions
• Center for hybrid and electric vehicles
• Center for smart healthcare research: medical systems and services

competence centers to establish in relevance to the different areas of sustainability are shown in Table 13:

Stakeholders, governance, and policy

The futures study is concerned with the pathway-oriented category of backcasting (e.g., Bengston et al. 2020; Wangel 2011), which entails identifying the actions and measures that connect a desirable state of the future to the present. At the core of this category in this context is how to bring about transformations to the landscape of the data-driven smart sustainable city of the future (Bibri and Krogstie 2021), supported with institutional practices and competences. Wangel (2011) classifies backcasting into several categories, namely pathway-oriented backcasting (how to change), target-oriented backcasting (what can change), action-oriented backcasting (who could make change happen), and participation-oriented backcasting (to enhance participation and buy-in by stakeholders). Accordingly. a detailed stakeholder analysis would rather be more relevant to action-oriented or participation-oriented backcasting. It is a way of studying a network in order to generate information on the relevant actors, "to understand their behaviour, interests, agendas, and influence on decision-making processes" (Reed et al. 2009), and to identify differing perspectives and avoiding conflicts (Prell et al. 2009). Also, the concept of governance is important when it comes to the actors involved in any transformative change. As argued by Wangel (2011, p. 881) with reference to action-oriented or participation-oriented backcasting, adding governance and actors in the backcasting study makes it "more socio-technically consistent and comprehensive," and can also identify if prevailing social structures restrain change. With the above in mind, the analytical account provided below is meant to help the reader gain some insights into how the concepts of stakeholder and governance together with politics and policy relate to the strategic planning process of transformative change towards sustainability from a general perspective.

Building the data-driven smart sustainable city of the future involves complex socio–technical constellations and configurations of a variety of urban, technological, scientific, social, political, cultural, and institutional actors interacting with and influencing each other on multiple scales and with different levels of complexity. At the core of this dynamic interplay is the engagement of many stakeholders in continuous dialogue to determine the programs associated with the development and implementation of the data-driven smart sustainable city of the future. Generally, the key stakeholders to be involved include: citizens, decision makers, policy makers, planners, developers, architects, experts, scientists, academics, scholars, researchers, professionals, business leaders, industrial engineering gurus, futurists, as well as civil society organizations. The data-driven smart sustainable city of the future is essentially dependent on the initiative by and interest of these stakeholders—that each sees it as of relevance and meaningfulness enough to play a role in a specific area—and that their initiatives should be coordinated so that they can complement and support each other for the purpose of developing and implementing data-driven technologies and solutions in development planning and operational management in order to balance and advance sustainability goals.

Furthermore, bringing about the necessary changes to attain the future vision requires engaging stakeholders in long-term cooperation, which is strongly dependent on the approach to their participation and management. The data-driven smart sustainable city of the future provides an opportunity that brings numerous stakeholders together and pool their substantive knowledge to put forth the relevant long-term plans that promote sustainable development in the era of big data. However, considering the time horizon of 25–50 years reasonably needed to develop the data-driven smart sustainable city as a desired future, coupled with the findings from the six cases investigated, the issue of uncertainty remains problematic. For example, it is unfeasible to make accurate, comprehensive top-down plans informed by bottom-up inputs from citizens for long-term cooperation. Moreover, as stakeholders usually have differing interests, it is necessary to develop and implement a framework for understanding and aligning their interests in ways to fit in with the newfound objectives of the government of a given city. The newfound objectives are associated with a rather more integrated approach to urban planning and development in regard to balancing and advancing the environmental, economic, and social goals of sustainability on the basis of the IoT and big data technologies. Such approach should be based on the opportunities, capabilities, and constraints of each city. While change has unpredictable consequences, the possibility for most of the stockholders to walk away as future winners is high as long as their alignment dovetails with the agenda of sustainable development and technological development. Moreover, in order to get all stakeholders on board, each city needs a tool to conceptualize long-term developments.

As a multifaceted process, governing the data-driven smart sustainable city of the future highlights how local government and stakeholders decide how to plan, finance, and manage urban areas, and involves a continuous process of negotiation and contestation over the allocation of technological, material, and social resources as well as political will and influence. In short, how different actors are engaged in the planning and steering of the city. While this increases public engagement and strengthen participatory and democratic processes, it can also lead to uncertainty and unpredictability in decision making. Maintaining the process of sustainable urban development towards achieving the goals of urban sustainability in the era of big data is an enormous challenge in terms of planning and management, and requires a collective approach to coordinating actions and decision–making processes, thereby the necessity of advanced forms of city governance and thus the importance of governance networks. Indeed, the kind of transformations associated with the data-driven smart sustainable city of the future calls for more open and inclusive models for city governance. In this regard, the city government needs to establish synergy between various actors and should, more importantly, invest in developing a bottom-up innovative ecosystem to engage citizens in a variety of ways. In managing urban transformations, the city government needs to play a strategic role in promoting participatory and democratic processes while forging partnerships with and among key stakeholders. The emerging forms of urban governance structures allow widespread participation of the citizenry by developing technologies that ensure shared knowledge for democratic governance and informed participation (see Bibri 2018 for a detailed analytical account in relation to data-driven smart sustainable cities of the future). However, the relationships among the stakeholders and institutions involved in city governance determine what happens in the city. City governance provides a means of understanding the relational dynamics between urban development and urban actors in the long term—in other words, the way governance networks work to maintain the process of urban development toward achieving the goals of sustainability. Governance networks function through various forms of network governance (whereby network is viewed as a mechanism of coordination) to promote sustainable development. Network coordination in public sector can provide considerable benefits, including enhanced learning, the efficient use of resources, increased capacity to plan for and address complex problems, and better services for citizens (Provan and Kenis 2007). The power and efficiency gains of governance networks derive from their distinctive features, namely:

- horizontal articulations of public, semi–public, and private actors that are dependent on one another's resources and capacities but operationally autonomous;
- these actors carry out negotiations within an institutionalized framework based on an amalgam of normative, cognitive, regulative, and imaginary elements;
- this framework is restricted by external forces as to its self–regulating patterns and actions; and
- its purpose is to contribute to the production of public purpose as an expression of plans, policies, and regulatory frameworks that are valid for, and directed towards, the general public.

The forms of coordination enabled by governance networks can be an apt response to the question of how to tackle complex policy problems and governance tasks in relation to the planning and development of the data-driven smart sustainable city of the future. This also justifies why governance networks need to be formed and why they can contribute to efficient governance within the field of policy and planning when it comes to sustainability transitions. However, governance networks are likely to fail on various counts due to otherwise inefficient coordination. Careful network governance is essential as it might prevent major dislocations and mitigate the impact of various disturbances; however, optimizing the functioning of governance networks on all dimensions is a daunting task (Klijn and Koppenjan 2004) and poses special conundrums.

Profoundly political, city governance is shaped and influenced by the creation and operation of political institutions and their mechanisms, government capacity to make and implement decisions and the extent to which these decisions secure and uphold environmentally sound, economically viable, and socially beneficial development through the synergistic integration of the more established strategies of sustainable cities and the more innovative solutions of data-driven smart cities towards achieving the long-term goals of sustainability. This envisioned outcome implies that the data-driven smart sustainable city of the future needs solid and effective policies that allow and regulate investments, partnerships, and developments of the kinds that contribute to and sustain its progress towards the sought goal. Here urban policies reflect fundamental social agreements about how the data-driven smart sustainable city of the future will continue to be built and transformed and how their inhabitants will relate to each other. Among the common mechanisms of political instilutions used in the operation that link the data-driven smart sustainable city of the future to political action are: creating regulatory and policy instruments and carrying out legislations; assigning scholarly roles and non-governmental institutional positions to particular universities and organisations (in terms of R&D activities, technology and innovation, policy recommendation, vision construction, and so on); orienting investments, supposing projects, providing incentives, advocating product and service adoption, organizing forums and symposiums, encouraging local and national programs, and creating comprehensive or master plans. Political institutions create, enforce, and apply or enact laws, and often mediate conflict and make policy on different societal systems. In this context, however, political processes represent the set-up under which dynamic networks of urban actors can interact within diverse urban sectors in the development, diffusion, and utilization of knowledge and technology pertaining to the data-driven smart sustainable city of the future.

The role of policy is associated with aligning and mobilizing different urban actors in the same direction in regard to the future vision. Worth pointing out is that the interactions between policy actors and the ability of policymaking mechanisms are affected by institutions as a set of factors (actions, rules, social structures, and practices) as to the adoption and implementation of effective responses to the various problems of policy in relation to sustainability and technology. Emergency problem is the first stage of the policy process, in addition to agenda setting, consideration of policy options, decision-making, implementation, and (6) evaluation (Jordan and Adelle 2012). Generally, institutions facilitate the coordination between a range of actors and networks, mediating the regulations and rules that govern those behaviors that are deemed of importance for society to make progress towards sustainability. Public policy consists of the set of actions—plans, laws, regulations, and behaviors—adopted by a city government. City governance draws attention to the extent to which these actions are often performed by city agents rather than directly by a city government, and also includes the relationships among the many players (stakeholders) involved and the goals of the city.

Discussion

Based on the four case studies conducted on the prevailing paradigms of sustainable urbanism and the emerging paradigms of smart urbanism, numerous benefits of the eco-city and the compact city have been realized and many potentials and opportunities of the data-driven smart city and the environmentally data-driven smart sustainable city are being unlocked and exploited. The purpose of their identification and enumeration is to highlight the added value of their combination within the framework of the data-driven smart sustainable city of the future in regard to boosting the benefits of environmental, economic, and social sustainability by means of integrating the design strategies and solutions of sustainable cities and smart cities.

Up till now, the four models of urbanism and investigated are regarded as weakly connected as approaches and more or less fragmented as landscapes at the technical and policy levels. The compact city and eco-city models, which have been around for over four decades or so, have many overlaps among them in their ideas, concepts, and visions, as well as distinctive concepts and key differences in terms of planning practices and design strategies. The overlap is justified by the fact that they both represent the central models of sustainable urbanism. As to the data-driven smart city, as an emerging paradigm of smart urbanism, it shares the challenges of sustainable development with the eco-city and compact city models, with the main difference being that it focuses more on the use and application of the IoT and big data technologies to overcome these challenges—than on the planning practices and design strategies of urban sustainability. Concerning the environmentally data-driven smart sustianable city model, it emphasizes the environmental dimension of sustainability and employs data-driven solutions to reach environmental targets. In this sense, it combines concepts and ideas from both the eco-city and the data-driven smart city. These models are increasingly being merged together on the basis of the IoT and big data analytics in a bid to confront the significant challenges posed by climate change in the face of urbanization. However, while they both implement data-driven solutions to improve and advance environmental sustainability, they remain significantly divergent with respect to their visions, policies, strategies, and priorities, thereby the meaningfulness and relevance of integrating their sustainable and technological solutions into one model.

While the environmental goals of sustainability tend to dominate in the discourse of the eco-city (e.g., Mostafavi and Doherty 2010; Holmstedt et al. 2017), the discourse of the compact city emphasizes the economic goals of sustainability (e.g., Bibri et al. 2020; Hofstad 2012; Jenks and Jones 2010), with the social goals of sustainability being of less focus in the eco-city than in the compact city (e.g., Bibri 2020; Lim and Kain 2016; Heinonen and Junnila 2011; Bramley and Power 2009; Rapoport and Vernay 2011). In view of that, it is of high relevance and importance to integrate the compact city and eco-city models so as to consolidate and harness their design strategies and sustainable technology solutions to deliver the best outcomes of sustainability. Their integration is indeed justified by the fact that the compact city needs to improve its environmental performance, that the eco-city needs to improve its social performance, and that both contribute differently to economic sustainability, with the former focusing on mixed-land use strategy and the latter on green-tech innovation strategy. Another argument supporting their integration is that they are compatible and not mutually exclusive. Some of the attempts undertaken to integrate these models tend to provide ideal approaches, to simply combine some ideas from each one of them to form new loosely integrated models, or to strengthen one model through adding principles from the other, all with the objective to incorporate the lacking or missing aspects of sustainability (e.g., Farr 2008; Harvey 2011; Jabareen 2006; Kenworthy 2019; Marcotullio 2017; Roseland 1997; Suzuki et al. 2010). However, as this work is more often than not based on design with respect to architecture and planning discipline, it emphasizes more on creativity, common sense, ideal target pursuit, and future scenarios, rather than fact-based evidence explanation, empirically grounded research, or scientific finding-oriented exploration.

The conscious push for sustainable cities to become smarter and thus more sustainable in the era of big data is due to the problematicity surrounding their development planning approaches and operational management mechanisms, as well as the fragmentation of their designs and techmologies related to compact cities and eco-cities as the most advocated models of sustainable urban form. This has a clear bearing on their performance with respect to the contribution to and balancing of the goals of sustainability. Indeed, over the last two decades, research within the field of sustainable urban forms, especially compact cities and eco-cities, has produced conflicting, uncertain, weak, and non-conclusive results (e.g., Bibri 2020b, c; Cugurullo 2016; Jenks and Dempsey 2005; Kaido 2005; Kärrholm 2011; Lim and Kain 2016; Neuman 2005; Williams 2010) concerning the actual benefits and effects these forms of human settlements claim to deliver. In this light, it has been argued that the dificiencies, shortcomings, struggles, and bottlenecks associated with sustainable cities are largely due to how they have long been studied, understood, planned, designed, and managed. This pertains to data scarcity, research methods with inherent limits and biases, long-term and static planning approaches, simulation models unable to deal with complex systems in terms of their design, and inefficient operational management mechanisms. This situation is dramatically changing thanks to the multifaceted potential of the IoT and big data analytics as the prerequisite enabling technologies of smart cities, nevertheless.

The technological strand of this study has been addressed in more detail in the two case studies conducted on the emerging paradigms of smart urbanism. One of the key aspects to highlight in regard to this strand is the role of smart cities in connecting the aforementioned infrastructures associated with the transformations needed to attain the future vision through the identified strategies and pathways. This connection is a way to leverage the collective intelligence of the data-driven smart sustainable city of the future through the synergic and substantive effects of advanced ICT with regard to increasing the benefits of sustainability. In other words, in making sustainable cities cleaner, safer, more resilient, and more efficient through urban computing and intelligence supporting joined-up and short term planning approaches. This can be accomplished by harnessing the vast troves of data that can be generated from across many urban domains thanks to advanced computational analytics techniques as well as urban operation systems and analytical centers (e.g., Ameer and Shah 2018, Batty et al. 2012; Bibri 2019a; Kitchin 2014, 2016; Nikitin et al. 2016, Rathore et al. 2016). Sustainable cities involve the kind of challenges that are enormous enough to call for a data-driven approach to planning as a function of many diverse city stakeholders. Joined-up planning is a form of integration and coordination that enables the city–wide effects associated with environmental, economic, and social sustainability to be monitored, understood, and embedded into the designs and responses of sustainable cities in terms of their operational functioning, I.e., forms, structures, spacial organisations, activities, and services as embedded in space and time.

However, sustainable cities are so characterized by their specificities as regards their compact and ecological dimensions and how and the extent to which these are integrated in a given city area or district. This in turn shapes the way in which the IoT and big data technologies can be embedded in the fabrics of sustainable cities, as well as how they can be applied in their operational management processes and development planning practices. In more detail, sustainable cities essentially exhibit key differences in the way they prioritize and implement their strategies and solutions, depending on many intertwined factors, notably physical, geographical, socio–political, economic, environmental, and historical. In particular, the IoT and big data technologies might work in one sustainable city in a way that is different in another. Hence, they should sometimes be dramatically reworked to be applicable in the context where they are embedded. Besides, sustainable cities do not have a unified agenda as a form of strategic planning, and data-driven decisions are unique to each sustainable city, so are environmental, economic, and social challenges. Big data are the answer, but each sustainable city sets its own questions based on what characterize it in regard to visions, policies, strategies, pathways, goals, and priorities. Regardless, it is important for sustainable cities to make the best use of their local opportunities and capabilities as well as to assess their potentials and constraints from a more integrated perspective when it comes to the operational management and development planning related to their compact, ecological, and technological landscapes and approaches.

Furthermore, the key institutional transformations needed to support the balancing of the three dimensions of sustainability and to enable the introduction of data-driven technologies and the adoption of applied data-driven solutions in city operational management and development planning were identified and enumerated with the objective to highlight the kind of changes that are required to develop and implement a functional model for data-driven smart sustainable cities of the future. A global trend at play today is the decentralization of the city management, where local authorities are becoming more and more empowered and resourceful to address and overcome the challenges of sustainability, whether in relation to sustainable cities or smart cities. In turn, in order for civic institutions to assume their increasing responsibility, they need to implement more effective frameworks for city development planning. Civic institutions are associated with some of the key issues that the data-driven smart sustainable city of the future should think about in improving the quality of urban environments, which include:

- Forming partnerships with civic institutions to use resources more efficiently and control them more safely, to promote more sustainable land use, and to preserve the biodiversity of natural ecosystems and reduce pressure on their services, with the ultimate aim to improve economic and societal outcomes. The latter involves achieving beneficial community effects, enhanced communication and interaction, and improved social well-being while boosting local economies and maximizing existing resources.
- Looking for short-term activities and temporary uses for institutions to meet the diverse needs of communities while capital funding is scarce. These new partnerships and ways of thinking about public resources provide a holistic and creative new approach to sustainability. They develop flexible urban places that may be used for a variety of functions to improve the quality of life for years to come.

- Promoting and engaging in cooperative planning around shared resources among diverse institutions.
- Working with local residents and stakeholders to come up with ideas to maximize the utilization of education and cultural facilities (universities, schools, municipal offices, etc).

Sustainable cities can use what smart cities have to offer in this regard to enhance their practices. This involves strengthening existing institutionalized practices and competences for supporting the balancing of the three dimensions of sustainability, as well as for developing and establishing new city management and development practices and competences in response to the latest innovations in data-driven technologies. These are increasingly becoming the main driving force of sustainable development in the era of urbanization. Data-driven technological innovations are nurturing or fostering "socio-technical configurations, which grow and displace incumbent regime activities" (Berkhout et al. 2003), as well as providing lessons and insights to policymakers to manage sustainability transitions. It remains to be seen if these transformative changes will be realized, which depends on the extent to which data-driven technological innovations will solve the challenges of sustainable urbanism and provide concrete value of sustainability. While data-driven technologies are bringing about massive changes to how sustainable cities can function by enabling them to monitor, analyze, model, and simulate their systems for better outcomes, the question is to what extent these developments will continue to be used meaningfully and to the collective advantage of citizens. Any potential disadvantages is yet to be seen as new advancements in artificial intelligence and the IoT will emerge together with new directions of their use. This is predicated on the assumption that all technological developments come with their dark side. Indeed, while big-data analytics and artificial intelligence can bring numerous advantages to urban sustainability, it is important to acknowledge the fact that these advanced technologies can be problematic, and therefore, policy-makers and planners should be careful when employing them. Many recent studies have discussed the potential urban problems and issues triggered by big-data analytics and artificial intelligence in the context of smart sustainable urbanism (e.g., Cugurullo 2020; Yigitcanlar and Cugurullo 2020).

Conclusion

Data-driven smart sustainable cities hold great potential to instigate major transformative changes on multiple scales by synergistically linking the agendas of urban development, sustainable development, and technological development to add a whole new dimension to sustainability. This analytical work presents a compilation of real-world experiences, successful practices, and positive outcomes in relation to sustainable urbanism and smart urbanism. The collection of the four case studies is intended to allow the reader to have a broad view on the types of technologies and solutions that could enhance and consolidate the design strategies and technology solutions of sustainable cities in ways that increase their contribution to the goals of sustainability.

This paper identified, distilled, and enumerated the key benefits, potentials, and opportunities of sustainable cities and smart cities with respect to the three dimensions of sustainability. Sustainable cities are always about citizens. Being data-driven smart about sustainable cities requires to connect directly to the concerns and needs of people concerning environmental protection, economic regeneration, and social equity. Historically, people have always moved to and preferred to live in sustainable cities to improve the quality of their lives, and smart urbanism is embraced anew as a strategic move to create sustainable cities that make urban living more sustainable over the long run—in short, that last. Towards this end, sustainable cities have to learn faster and identify strategic pathways to achieve synergistic and balanced effects of sustainability through integrating their design strategies and technology solutions with the emerging data-driven technolgies and solutions of smart cities. These effects involve the benefits that should be increased, the potentials that should be exploited, and the opportunities that should be explored in the ambit of the data-driven smart sustainable city of the future. Indeed, this emerging paradigm of urbanism is generating worldwide attention as a powerful framework for strategic sustainable urban development, thereby gaining momentum as an academic discourse and thus settling into institutional structures and new practices and competences.

This paper also identified, distilled, and enumerated the key institutional transformations needed to support the balancing of the dimensions of sustainability and to enable the introduction of data-driven technology and the adoption of applied data-driven solutions in city operational management and development planning. The identified institutional practices and competences are framed within the data-driven smart sustainable city of the future. Therefore, they are intended to reinforce and complement each other in the endeavor to balance and advance the goals of sustainbility. This requires developing and implementing an institutional framework, the systems of formal laws, regulations, and procedures as well as stakeholders with their roles and informal conventions and norms, that shape socioeconomic activities and behaviors. This framework is a prerequisite for the successful implementation of advanced city operational management and development planning intervention projects and initiatives for enabling the functioning of the data-driven smart sustainable city of the future. The essence of this new integrated model lies in providing the needed tools, techniques, methods, systems, platforms, and infrastructures enabled by the core enabling and driving technologies of the IoT and big data analytics for sustainable cities to have a more measurable, targeted, and hormonized contribution to sustainability. This in turn means finding and applying more effective ways of translating sustainability into the physical, spatial, environmental, economic, and social forms of the city.

Abbreviations

GHG: GreenHouse Gases; ICT: Information and Communication Technology; IoT: Internet of Things; SDG: Sustainable Development Goal

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Publisher's Note

Appendix B: Secondary Papers

The publications presented in Appendix B were written during both the PhD study and write-up process. The first two papers concern the theoretical and disciplinary foundations of the futures study. The last two papers concern the strategic and innovative planning approaches associated with the design and development of data-driven smart sustainable cities of the future.

P1: Bibri, Simon Elias: "The Sciences Underlying Smart Sustainable Urbanism: Unprecedented Paradigmatic and Scholarly Shifts in Light of Big Data Science and Analytics". Smart Cities 2019; Volume 2.(2) pp. 179–213

P2: Bibri, Simon Elias: "The Core Academic and Scientific Disciplines Underlying Data-Driven Smart Sustainable Urbanism: An Interdisciplinary and Transdisciplinary Framework". Journal of Computational Urban Science 2021. Volume 1. (1) pp. 1-32.

P3: Bibri, Simon Elias: "Data-driven Smart Sustainable Cities of the Future: Urban Computing and Intelligence for Long-term, Short-term, and Joined-up Planning of Complex Systems". Journal of Computational Urban Science 2021 (In Press)

P4: Bibri, Simon Elias: "Data-Driven Smart Sustainable Cities of the Future: New Conceptions of and Approaches to the Spatial Scaling of Urban Form". Future Cities and Environment 2021, Volume 7. (1) pp. 1–15

DECLARATION OF CO-AUTHORSHIP

Declaration of co-authorship is to be included when a thesis containing papers written by more than one author must include this signed declaration that describes the contribution of the candidate and the co-authors of each of the papers. It must be possible to identify the candidate's independent contribution in the work.
(cf. the PhD regulations section 10 or dr.philos regulations section 3).

Name of candidate:
Simon Elias Bibri

Title of dissertation:
A Novel Model for Data-Driven Smart Sustainable Cities of the Future: A Strategic Planning Process of Transformative Change towards Sustainability

Publications:

1. Bibri, Simon Elias and Krogstie, John: "Smart Sustainable Cities of the Future: An Extensive Interdisciplinary Literature Review". Sustainable Cities and Society 2017; Volume (31) s.183-212

2. Bibri, Simon Elias and Krogstie, John: "A scholarly backcasting approach to a novel model for smart sustainable cities of the future: strategic problem orientation ". Journal of Futures Studies 2019; Volume 6.(3) s. 1-27

3. Bibri, Simon Elias and Krogstie, John: "Generating a Vision for Smart Sustainable Cities of the Future: A Scholarly Backcasting Approach", European Journal of Futures Research; Volume 7.(5) s. 1-20.

4. Bibri, Simon Elias, Krogstie, John and Kärrholm, Mattias: "Compact City Planning and Development: Emerging Practices and Strategies for Achieving the Goals of Sustainability". Developments in the built environment 2020; Volume 4 s. 1-20

5. Bibri, Simon Elias and Krogstie, John: "Smart Eco–City Strategies and Solutions: The Cases of Royal Seaport, Stockholm, and Western Harbor, Malmö". Urban Science 2020; Volume 4.(1) s. 1-42.

6. Bibri, Simon Elias and Krogstie, John: "The emerging Data–driven Smart City and its Innovative Applied Solutions for Sustainability: The cases of London and Barcelona". Journal of Energy Informatics 2020; Volume (3).5 s. 1-42

7. Bibri, Simon Elias and Krogstie, John: "Environmentally Data-driven Smart Sustainable Cities: Applied innovative Solutions for Energy Efficiency, Pollution Reduction, and Urban Metabolism". Energy Informatics 2020; Volume (3).29 s. 1-59

8. Bibri Simon Elias and Krogstie John: "Data-Driven Smart Sustainable Cities of the Future: A Novel Model of Urbanism and its Core Dimensions, Strategies, and Solutions". Journal of future Studies; Volume 25(2). s. 77–94

9. Bibri, Simon Elias and Krogstie John: "A Novel Model for Data-Driven Smart Sustainable Cities of the Future: A Strategic Roadmap to Transformational Change in the Era of Big Data" . Future Cities and Environment; Volume 7(1).3 s. 1–25
.

Description of the Candidate's Contribution:
Simon Elias Bibri wrote the above listed papers, and John Krogstie provided comments and suggestions for improvements prior to the review process.

Statement by the co-author:
I hereby confirm that the doctoral candidate's described contributions to Paper 1-9 is correct, and I consent to including them in the named dissertation.

Place, Trondheim 04.03.2021

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NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

DECLARATION OF CO-AUTHORSHIP

Declaration of co-authorship is to be included when a thesis containing papers written by more than one author must include this signed declaration that describes the contribution of the candidate and the co-authors of each of the papers. It must be possible to identify the candidate's independent contribution in the work.

(cf. the PhD regulations section 10 or dr.philos regulations section 3).

Name of candidate:
Simon Elias Bibri

Title of dissertation:
A Novel Model for Data-Driven Smart Sustainable Cities of the Future: A Strategic Planning Process of Transformative Change towards Sustainability

Publication:

Bibri, Simon Elias, Krogstie, John and Kärrholm, Mattias: "Compact City Planning and Development: Emerging Practices and Strategies for Achieving the Goals of Sustainability". Developments in the built environment 2020; Volume 4 s. 1-20

Description of the Candidate's contribution:
Simon Elias Bibri wrote the entire paper, and Mattias Kärrholm provided comments prior to the review process.

Statement by the co-author:
I hereby confirm that the doctoral candidate's described contribution to the paper is correct, and I consent to including it in the named dissertation.

Place, Lund 04.03.2021

Prof. Mattias Kärrholm