Journal of Futures Studies
2020,Vol. 25(2) 77–94
DOI: 10.6531/JFS.202012_25(2).0009

Article

Data-Driven Smart Sustainable Cities of the Future: A Novel Model of Urbanism and Its Core Dimensions, Strategies, and Solutions

Simon Elias Bibri[1,2,*], John Krogstie[1]

[1]*Department of Computer Science, The Norwegian University of Science and Technology, Saelands veie 9, NO–7491 Trondheim, Norway*
[2]*Department of Architecture and Planning, The Norwegian University of Science and Technology, Alfred Getz vei 3, Sentralbygg 1, 5th floor, NO–7491 Trondheim, Norway*

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.

* *Corresponding author*.
E-mail addresses: simoe@ntnu.no (S. E. Bibri), john.krogstie@ntnu.no (J. Krogstie).

Received: 29 Aug. 2020 and Accepted: 25 Nov. 2020

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.

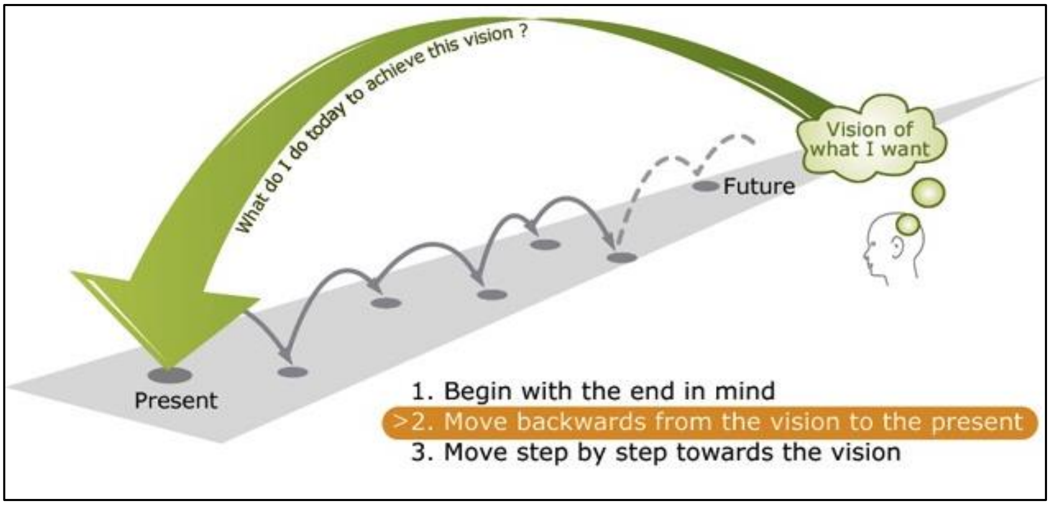

Fig. 1: The backcasting process from the Natural Step Source: Holmberg (1998)

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.

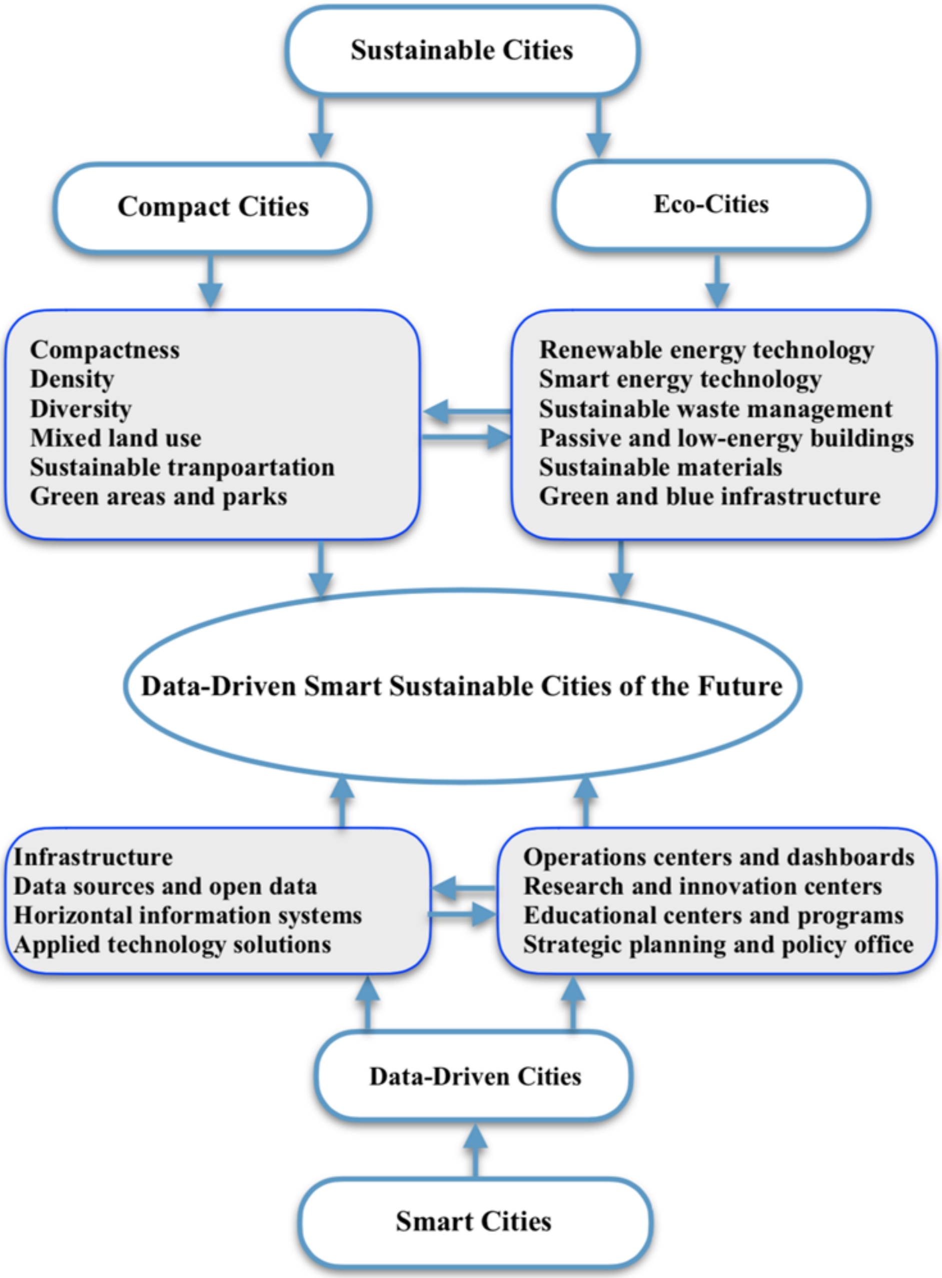

Fig. 2: A framework for strategic sustainable urban development planning

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.

Acknowledgements

The authors received no financial support for the research, authorship, and/or publication of this article. The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

Al Nuaimi, E., Al Neyadi, H., Nader, M., & Al-Jaroodi, J. (2015). Applications of big data to smart cities. *Journal of Internet Services and Applications*, *6* (25), 1-15.

Batty, M., Axhausen, K. W., Giannotti, F., Pozdnoukhov, A., Bazzani, A., Wachowicz, M., Ouzounis, G., & Portugali, Y. (2012). Smart cities of the future, *European Physical Journal, 214*, 481-518.

Bettencourt, L. M. A. (2014). The uses of big data in cities. Santa Fe Institute, Santa Fe, New Mexico.

Bibri, S. E. (2018a). *Smart sustainable cities of the future: The untapped potential of big data analytics and context aware computing for advancing sustainability*. Germany: Springer.

Bibri, S. E. (2018b). The IoT for smart sustainable cities of the future: an analytical framework for sensor-based big data applications for environmental sustainability. *Sustainable Cities and Society, 38,* 230-253.

Bibri, S. E. (2018c). Backcasting in futures studies: A synthesized scholarly and planning approach to strategic smart sustainable city development. *European Journal of Futures Research*, *6*(13), 1-27.

Bibri, S. E. (2018d). A foundational framework for smart sustainable city development: theoretical, disciplinary, and discursive dimensions and their synergies. *Sustainable Cities and Society*, *38*, 758-794.

Bibri, S. E. (2019a). *Big data science and analytics for smart sustainable urbanism: unprecedented paradigmatic shifts and practical advancements*, Netherlands: Springer.

Bibri, S. E. (2019b). The anatomy of the data-driven smart sustainable city: Instrumentation, datafication, computerization and related application, *Journal of Big Data*, *6*(59), 1-43.

Bibri, S. E. (2019c). On the sustainability of smart and smarter cities and related big data applications: An interdisciplinary and transdisciplinary review and synthesis. *Journal of Big Data*. *6*(25), 1-64.

Bibri, S. E. (2019d). The Sciences Underlying Smart Sustainable Urbanism: Unprecedented Paradigmatic and Scholarly Shifts in Light of Big Data Science and Analytics, *Smart Cities 2*(2), 179–213.

Bibri, S. E. (2020a). *Advances in the Leading Paradigms of Urbanism and their Amalgamation: Compact Cities, Eco–cities, and Data–Driven Smart Cities,* Switzerland, Springer Nature.

Bibri, S. E. (2020b). The Eco-city and Its Core Environmental Dimension of Sustainability: Renewable and Data-Driven Smart Energy Technology Solutions and their Integration, *Energy Informatics* (in press).

Bibri, S. E. (2020c). Compact urbanism and the synergic potential of its integration with data-driven smart urbanism: An extensive interdisciplinary literature review, Journal of Land Use Policy, vol. 97, p. 1-20.

Bibri, S. E. (2020d). 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, In Press

Bibri, S. E. (2020e). Data-driven environmental solutions for smart sustainable cities: strategies and pathways for energy efficiency and pollution reduction. *Euro-Mediterr J Environ Integr 5*(66)

Bibri, S. E., & Krogstie, J. (2016). On the social shaping dimensions of smart sustainable cities: A study in science, technology, and society, *Sustainable Cities and Society, 29*, 219–246.

Bibri, S. E., & Krogstie, J. (2017a). Smart sustainable cities of the future: An extensive interdisciplinary literature review. *Sustainable Cities and Society*, *31*, 183-212.

Bibri, S. E., & Krogstie, J. (2017b). ICT of the new wave of computing for sustainable urban forms: Their big data and context-aware augmented typologies and design concepts. *Sustainable Cities Society*, *32*, 449-474.

Bibri, S. E., & Krogstie, J. (2017c). The core enabling technologies of big data analytics and context–

aware computing for smart sustainable cities: A Review and synthesis, *Journal of big Big Data*, *4*(38), 1–50.

Bibri, S. E., & Krogstie, J. (2018). The big data deluge for transforming the knowledge of smart sustainable cities: a data mining framework for urban analytics, Proceedings of the 3d annual international conference on smart city applications, ACM, Oct 11–12, Tetouan, Morocco.

Bibri, S. E., & Krogstie, J. (2019a). A scholarly backcasting approach to a novel model for smart sustainable cities of the future: Strategic problem orientation, *City, Territory, and Architecture*, *6*(3), 1-27.

Bibri, S. E., & Krogstie, J. (2019b). Generating a Vision for Smart Sustainable Cities of the Future: A Scholarly Backcasting Approach, *European Journal of Futures Research*, *7*(5), 1-20.

Bibri, S. E., & Krogstie, J. (2020a). Smart eco–city strategies and solutions: The cases of Royal Seaport, Stockholm, and Western Harbor, Malmö, Sweden, *Urban Science*, *4*(1), 1-42.

Bibri, S. E., & Krogstie, J. (2020b). The emerging data–driven smart city and its innovative applied solutions for sustainability: The cases of London and Barcelona, *Journal of Energy Informatics* (in press).

Bibri, S. E., & Krogstie, J. (2020c). Environmentally Data-driven smart sustainable cities: Applied innovative solutions for energy efficiency, pollution reduction, and urban metabolism, *Energy Informatics*, In Press

Bibri, S. E., Krogstie, J., & Kärrholm, M. J. (2020). Compact city planning and development: Emerging practices and strategies for sustainable development goals, *Developments in built environment* (in press).

Burton, E. (2002). Measuring urban compactness in UK towns and cities , *Environment and Planning B: Planning and Design*, 29, 219 – 250

Dempsey, N. (2010). Revisiting the Compact City?, *Built Environment 36*(1), 5 – 8.

Dreborg, K. H. (1996). Essence of backcasting. *Futures*, *28*(9), 813-828.

Hofstad, H. (2012). Compact city development: High ideals and emerging practices. *European Journal of Spatial Planning*, *49*, 1-23.

Höjer, M., & Wangel, S. (2015). Smart sustainable cities: definition and challenges. In L. Hilty & B. Aebischer B (Eds.), *ICT innovations for sustainability*. (pp.333-349). Berlin: Springer.

Holmberg, J. (1998). Backcasting: A natural step in operationalizing sustainable development. *Greener Management International* (GMI), *23*, 30-51.

Iverot, S. p., & Brandt, N. (2011). The development of a sustainable urban district in Hammarby Sjöstad, Stockholm, Sweden?, *Environment, Development and Sustainability*, *13*(6), 1043-1064.

Jabareen, Y. R. (2006). Sustainable urban forms: Their typologies, models, and concepts. *Journal of Planning Education Research*, *26*, 38-52.

Jenks, M., & Dempsey, N. (2005). *Future Forms and Design for Sustainable Cities*, Oxford: Elsevier.

Jenks, M., & Jones, C. (Eds.) (2010). Dimensions of the sustainable city. London: SpringerLink.

Joss, S., Cowley, R., & Tomozeiu, D. (2013). Towards the ubiquitous eco-city: An analysis of the internationalisation of eco-city policy and practice. *Journal of Urban Research and Practice*, *76*, 16-22.

Lim, H. K., & Kain, J. H. (2016). Compact cities are complex, intense and diverse but: Can we design such emergent urban properties? Urban Planning, *1*(1), 95.

Mostafavi, M., & Doherty, G. (2010). *Ecological Urbanism*. Switzerland: Lars Muller.

Nikitin, K., Lantsev, N., Nugaev, A., & Yakovleva, A. (2016). Data-driven cities: From concept to applied solutions. PricewaterhouseCoopers (PwC), http://docplayer.net/50140321-From-concept-to-applied-solutions-data-driven-cities.html

Pasichnyi, O., Levihn, F., Shahrokni, H., Wallin, J., & Kordas, O. (2019). Data- driven strategic planning of building energy retrofitting: The case of Stockholm. J Clean Prod *233*,546–560

Rapoport, E., & Vernay, A. L. (2011). Defining the eco-city: A discursive approach. In Paper presented at the management and innovation for a sustainable built environment conference, international eco-cities initiative, Amsterdam, The Netherlands, pp.1-15.

Shahrokni, H., Levihn, F., & Brandt, N. (2014). Big meter data analysis of the energy efficiency potential in Stockholm's building stock, *Energy and Buildings*. *78*, 153–164.

Shahrokni, H., van der Heijde, B., Lazarevic, D., & Brandt, N. (2014). Big data GIS analytics towards efficient waste management in Stockholm. In *ICT4S–ICT for Sustainability*. Stockholm: Alantis Press.

Shahrokni, H., Årman, L., Lazarevic, D., Nilsson, A., & Brandt, N. (2015). Implementing smart urban metabolism in the Stockholm Royal Seaport: smart city SRS. *Journal of Industrial Ecology*, *19*(5), 917-929.

Shahrokni, H., Lazarevic, D., & Brandt, N. (2015). Smart Urban Metabolism: Towards a real-time understanding of the energy and material flows of a city and its citizens, *Journal of Urban Technology*, *22*(1), 65–86.

Stake, R. E. (2006). *Multiple case study analysis*, New York: Guilford.

United Nations. (2015a). Transforming our world: the 2030 agenda for sustainable development, New York, NY. Available at: https://sustainabledevelopment.un.org/post2015/transformingourworld

United Nations. (2015b). Habitat III Issue Papers, 21—Smart cities (V2.0), New York, NY. Available at: https://collaboration.worldbank.org/docs/DOC–20778. Accessed 2 May 2017

United Nations. (2015c). Big Data and the 2030 agenda for sustainable development. Prepared by A. Maaroof. Available at: www.unescap.org/events/call–participants–big–data–and–2030–agendasustainable–development–achieving–development

Vergragt, P. J., & Quist, J. (2011). Backcasting for sustainability: Introduction to the special issue 1, *Technological Forecasting and Social Change*, *78*(5), 747-755.

Wangel, J. (2011). Exploring 'the social' in backcasting studies for sustainable development, *Technological Forecasting and Social Change*, This Issue.

Williams, K. (2010). Sustainable cities: research and practice challenges. *International Journal of Urban Sustainable Development*, *1*(1), 128-132.

Wieviorka, M. (1992). 'Case Studies: History or Sociology?' in Ragin, Charles C. and Becker, Howard S. (eds), What is a Case? *Exploring the Foundations of Social Inquiry*. *Cambridge*: Cambridge University Press, pp. 159–172.

Yin, R. K. (2017). Case study research and applications (6th ed.): Design and Methods, SAGE Publications Inc.