

TECHNICAL ARTICLE

Data-Driven Smart Sustainable Cities of the Future: New Conceptions of and Approaches to the Spatial Scaling of Urban Form

Simon Elias Bibri^{*,†}

There is a growing interest in urban form as the spatial concretization of urban sustainability. At the core of sustainable urban form is the spatial pattern of the different types of the physical objects characterizing the built-up areas of settlements at different spatial scales. The spatial features of urban design is key to producing the benefits of sustainability and enacting its effects as outcomes of processes. However, it has been difficult to evaluate how and to what extent sustainable urban forms contribute to sustainability and to judge whether or not a certain sustainable urban form is actually sustainable. Therefore, there is a need to find more effective ways to address and implement the spatial scaling of sustainable urban form in an attempt to increase the positive outcomes of sustainability. This relates to the emerging model of sustainable cities, which is increasingly being enabled by urban computing and intelligence in terms of planning and design under what has been termed “data-driven smart sustainable cities”. This paper analyzes and discusses the emerging conceptions of and approaches to spatial scales that should be considered in the planning and design of data-driven smart sustainable cities of the future. In doing so, it highlights the innovative potential of urban computing and intelligence for enhancing and transforming the spatial scaling of sustainable urban form. I argue that data-driven technologies allow sustainable urban forms to monitor, understand, and analyze the different aspects of their spatial scaling for generating the kind of designs that improve sustainability. Conceiving spatial scales as outcomes of processes and planning accordingly hold great potential for attaining the goals of sustainability. Sustainability outcomes are multi-scalar in nature, which justifies the need to integrate spatial scales that have clear synergies in their management and planning and need to be coupled. This synergic integration produces combined effects that are greater than the sum of the separate effects of spatial scales with respect to sustainability benefits.

Keywords: Data-driven smart sustainable cities of the future; sustainable urban forms; spatial scales; planning; design; urban intelligence; big data technologies

1. Introduction

The increased pressure on cities has led to a stronger need to build sustainable cities that last. Designing sustainable cities of the future, educated by the lessons of the past and anticipating the challenges of the future, entails articulating a multi-scalar vision and following key principles—energy, ecology, infrastructure, waste, water, livability, mobility, accessibility, economy, and culture—while responding to macro-shifts along the way. These principles are at the core of urban sustainability, which

represents an ideal outcome in the sum of all the goals of development planning, on which there is widespread consensus with trade-offs and conflicts when it comes to making decisions. 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; Ihlebæk, Næss and Stefansdottir 2020; 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 in 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

* Department of Computer Science, Norwegian University of Science and Technology, Sem Sælands vei 9, NO-7491 Trondheim, NO

† Department of Architecture and Planning, Norwegian University of Science and Technology, Alfred Getz vei 3, Sentralbygg 1, 5th floor, NO-7491 Trondheim, NO

simoe@ntnu.no

with inherent limitations, biases, and constraints, often as a result of relying on selective samples.

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.

In addition, the stable relationships between a set of sustainable activities and a certain urban form are not easily generalizable on the basis of form–function (Kärholm 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, Kärholm (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).

There is an increasing interest in urban form as the spatial concretization of urban sustainability. At the core of sustainable urban form is the spatial pattern of the various forms of the physical objects characterizing the built-up areas of settlements at different spatial scales. The spatial is key to generating the benefits of sustainability as to its tripartite value. The existing models of sustainable urban form, particularly compact cities and eco-cities, have positive outcomes as to contributing to

the three goals of sustainability (e.g., Bibri and Krogstie 2020a; Bibri, Krogstie and Kärholm 2020; Burton 2000, 2002; Dempsey 2010; Dempsey and Jenks 2010; Hofstad 2012; Jenks and Dempsey 2005; Jenks and Jones 2010; Joss 2011; Kenworthy 2006; Rapoport and Vernay 2011; Suzuki et al. 2010) In recent years, it is of crucial importance to find more effective ways to address and implement the spatial scaling of sustainable urban form in an attempt to increase the positive outcomes of sustainability. This relates to the emerging model of sustainable cities, which is increasingly being enabled by urban computing and intelligence in terms of planning and design as well as operational management under what has been termed “data-driven smart sustainable cities of the future” (Bibri 2021a, b).

This paper analyzes and discusses the emerging conceptions of and approaches to spatial scales that should be considered in the planning of data-driven smart sustainable cities of the future. In doing so, it highlights the innovative potential of urban computing and intelligence for enhancing and transforming the spatial scaling of sustainable urban form. This paper expands on prior work done to develop a novel model for data-driven smart sustainable cities of the future in the form of a strategic roadmap towards transformational change (Bibri and Krogstie 2021). This new model of urbanism is grounded in the four case studies that were conducted on the prevailing paradigms of sustainable urbanism and the emerging paradigms of smart urbanism, namely:

- compact cities (Bibri et al. 2020);
- smart 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 paper is structured as follows: Section 2 provides the definitions of the key concepts underlying this study. Section 3 focuses on the research methodology as to the case studies informing this study. Section 4 presents the results in terms of analysis and discussion. This paper, ends in, Section 5, with a summary of the key points together with some critical perspectives.

2. Theoretical Background

2.1. Urban Form

It is useful to operationalize the term “urban form” as it is not easy to define. Urban form refers to the physical characteristics that make up the built-up areas in a city, including the shape, size, design, and configuration of settlements. The aggregation of these more or less repetitive elements represents urban patterns, which give a regular form to the physical objects in a city. Lynch (1981, p. 47) defines urban form as “the spatial pattern of the large, inert, permanent physical objects in a city.” Urban patterns are made up largely of a limited number of relatively undifferentiated types of elements. Thus, they have strong similarities and can be grouped into concepts (Lozano 1990) that comprise such components as

building density and scale, block size and shape, street design and pattern, lot configuration, public space, and park layout (Jabareen 2006). Urban form can be considered at different spatial scales, including regional, metropolitan, urban, municipal, neighbourhood, street, and block.

2.2. Spatial Scale

The concept of spatial scale relates to urban geography and architectural discourses (Boudon 1999; Lawson 2001; Yaneva 2005). In geography, spatial scale classifies, with large approximation, the size of a land area. It is the extent of an area at which a phenomenon or a process occurs. According to Bibri (2020a), scale is both the order of magnitude of a land area that shapes process and the order of magnitude of a land area that emerges from a process. The working definition in this paper is based on Caniggia and Maffei's Architectural Composition that defines scale as "different level of complexity of the components internally arranged to construct a whole" (Caniggia and Maffei 2001, p. 245). The scales considered in the ambit of data-driven smart sustainable cities of the future are to be addressed as relationships between spaces of different dimensions, where the "constructed whole" of one scale can be a mere "component among components" at another (Caniggia and Maffei 2001). Smith (2003, p. 228) describe scales as "materially real frames of social action" and socially constructed and materially produced, and also conceives of scales as "the spatial resolution of contradictory social forces."

2.3. Sustainable Urban Form

The form of the city is seen as a salient factor for enacting more sustainable, efficient, equitable, and livable urban environments through compact and ecological design. 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 new global trends at play today. In *Achieving Sustainable Urban Form*, Williams, Burton and Jenks, (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. However, management tends to dominate within the eco-city, unlike the compact city where design is at the core of compaction strategies. That is to say, 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. Still, these two models of sustainable urban form share several concepts, ideas, and visions (e.g., Bibri and

Krogstie 2020a; Farr 2008; Jabareen 2006; Kenworthy 2019; Marcotullio 2017; Roseland 1997; Suzuki et al. 2010). Furthermore, urban form is associated with the development and design strategies related to the dimensions of urbanization, namely physical (land use change), geographical (population), economic (agglomeration), and societal (social and cultural change). Such strategies are at the core of compact cities and eco-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. Most of the existing definitions of the compact city tend to be associated with the wider socio-cultural context in which the compact city model is embedded in the form of projects and initiatives and related objectives, requirements, resources, and capabilities (see, e.g., Hofstad 2012; Bibri, Krogstie and Kärrholm 2020). This also applies to the eco-city in terms of the practices and strategies adopted to achieve the goals of environmental sustainability. The idea of the eco-city is widely varied in conceptualization and operationalization. An eco-city is "an urban environmental system in which input (of resources) and output (of waste) are minimized" (Register 1987). According to Jabareen (2006, pp. 46–47), the eco-city "is 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." Roseland (1997) argues that there is no single accepted definition of the eco-city, but more a collection of ideas about concepts. Joss (2010) substantiates the conceptual diversity and plurality of the initiatives and projects using the term across the globe.

2.4. Data-Driven Smart Sustainable Cities

In the context of this 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 and advance their contribution to the goals of sustainability on the basis of the innovative data-driven technologies and solutions offered by smart cities. Bibri and Krogstie (2021) specify the set of targets that need to be reached in order to attain the status of data-driven smart sustainable cities of the future (**Table 1**). These targets are based on the synergistic integration of the strategies and solutions of the aforementioned paradigms of urbanism. (Bibri 2021b) provides a comprehensive state-of-the-art literature review of the flourishing field of data-

Table 1: The core compact, ecological, and technological targets of data-driven smart sustainable cities.

<ul style="list-style-type: none"> • 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: <ul style="list-style-type: none"> – 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: <ul style="list-style-type: none"> – 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.
--

driven smart sustainable cities, including the definitions, dimensions, and strategies of the underlying paradigms of urbanism, namely sustainable cities, eco-cities, compact cities, smart cities, data-driven cities, and smart sustainable cities.

A data-driven smart sustainable city is 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 decisions that accurately address the problems, issues, and challenges related to sustainability and urbanization. The emerging data-driven solutions can be adopted by city management agencies and city planning and policy centers to improve sustainability, efficiency, resilience, equity, and the quality of life. Underlying data-driven smart sustainable cities is a number of platforms and centers associated with technical and institutional competences and practices (see Bibri 2021c for a descriptive account), 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. This paper is associated with some of the aspects of development planning

in relation to the spatial scaling of sustainable urban form.

2.5. Urban Intelligence

Urban intelligence refers to the planning, development, deployment, implementation, and maintenance of the ecosystem of big data analytics to support the interoperability between resources and technologies—and thus the integration of urban systems, the coordination of urban domains, and the coupling of urban networks—to serve the stakeholders of the city. Its functions entail the use of big data analytics and the underlying core enabling technologies to devise more effective solutions in the form of designs and responses using advanced simulation models, optimization methods, and intelligent decision support systems. This requires urban environments to be digitally instrumented to generate the data deluge that enables real-time analysis of the operating and organizing processes of urban life—urban computing. The knowledge extracted as a result of data deluge analytics serves to optimize and enhance the operations, functions, services, designs, strategies, and policies in line with the long-term vision of sustainability thanks to urban intelligence and planning functions as an advanced form of decision support.

Urban computing and intelligence (e.g., Batty et al. 2012; Bibri 2021a; Bibri and Krogstie 2017; Lynch and Del Casino Jr 2020; Ji, Zheng and Li 2016; Liu et al. 2017; Zheng et al. 2014; Zheng et al. 2015; Zhang and Zheng 2016) has recently attracted significant attention from academia and industry for building data-driven smart sustainable cities of the future. It represents a holistic approach to harnessing and exploiting the vast troves of big data generated in cities to improve urban forms, urban infrastructures, urban environments, and urban services, as well as urban operational management and development planning systems. As such, it can generate deep insights that can be used to make well-informed and fact-based decisions, and can also create feedback loops between humans and their activities and the urban environment.

3. Research Methodology

As mentioned earlier, this article expands on prior work done to develop a 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 three main phases of this process—(1) the constructed future vision, (2) the specified objectives and targets related to sustainability, and (3) the developed strategies and pathways for transformative change—are grounded in case study research (Bibri and Krogstie 2021). This was carried out on a total of six of the ecologically and technologically leading cities in Europe. The case study approach, which is associated with the empirical phase of the futures study, was adopted to examine and compare two cases with respect to each of the phenomena of compact cities, smart eco-cities, data-driven smart cities, and environmentally data-driven smart sustainable cities. Bibri (2020d) dedicates a whole article to the methodological framework applied in the futures study, which combines a set of principles underlying several normative backcasting approaches as well as descriptive case study design.

The latter is what this article is concerned with in terms of empirically informing the analysis of the new conceptions of and approaches to spatial scaling associated with the development and design of data-driven smart sustainable cities of the future.

The case study is a descriptive qualitative approach 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 approach for the empirical basis of the futures study. 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 six cities selected behave as to what has been realized, the ongoing implementation of plans, and the execution of projects 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 2**).

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 technologies, 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.
-

The four case studies investigated contemporary real-world phenomena with the objective 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 era of big data and in the face of urbanization. They were 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. Overall, the four case studies conducted were useful for illuminating the different phenomena of urbanism, for illustrating the general principles underlying these phenomena, and for generating new ideas and research questions involving the relationships between these phenomena.

4. Results: Analysis and Discussion

The analysis and discussion presented in this paper are intended to inform the strategic planning process of transformative change towards sustainability, or to enhance the novel model for data-driven smart sustainable cities of the future in terms of its development and design. The essence of this integrated model of urbanism 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 harmonized contribution to sustainability. This in turn means finding and applying more effective ways of translating sustainability into the spatial, physical, environmental, economic, and social forms of sustainable cities with regard to planning and design. The spatial aspects of sustainable urban form is what this paper is concerned with.

4.1. Urban Intelligence and Planning Functions for Urban Forms and their Spatial Scaling

This paper relates to a recent study that analyzes the enabling role and innovative potential of urban computing and intelligence in the strategic, short-term, and joined-planning of data-driven smart sustainable cities of the future (Bibri 2021a). In this study, it is argued that the fast-flowing torrent of urban data, coupled with its analytical power, is of crucial importance to the effective planning and design of data-driven smart sustainable cities of the future thanks to the advanced form of intelligent decision support enabled by urban computing and intelligence. This pertains particularly to the powerful new forms of simulation models and optimization methods that can be constructed by means of utilizing, integrating, and harnessing complexity science, urban complexity theories, sustainability science, urban sustainability theories, urban science, and big data analytics following the fundamental principles of data science and data-intensive science. These models and methods can generate the kind of designs and responses characterizing the operations and functions of sustainable urban form that improve sustainability, efficiency, resilience, equity, and life quality. These designs and responses involve urban forms, urban structures, spatial organizations, and spatial scales. They are developed by innovation labs, which acquire, process,

and analyze data from multiple, heterogenous sources to extract useful knowledge in the form of applied intelligence associated with the strategies and practices of urban sustainability. These urban intelligence labs work directly with various urban actors (government agencies, public authorities, organizations, institutions, companies, communities, and citizens, etc.), with the objective solving tangible and significant problems of urban planning and design through enhanced decision-making processes. This involves delivering the problem-oriented research that advances the scientific understanding of the city with respect to sustainability and urbanization and how they intertwine with and influence each other, and that directly reshapes and impacts decision-making in the sense of enhancing urban planning and design practices and solving urban problems.

With the projected advancements and innovations in urban computing and intelligence, the process of development urban intelligence and planning functions will shift from top-down (expert and professional organizations) to engaging citizens with experts in response to the problematicity surrounding the planning of data-driven smart sustainable cities of the future. This entails integrating databases and models from across various urban domains in order to support the development of this sort of integrated intelligence functions, with new or refashioned ways at different levels, including the visualization of data and sustainability problems, the use of tools for informing and predicting the impacts of future sustainability scenarios, and the involvement of citizens and their relevant recommendations, all into a form of a holistic system that operates at different spatial scales and over different temporal scales. Urban intelligence labs collaborate closely with the policy and strategic planning office as an analytical center that constitutes a key competence of data-driven smart sustainable cities of the future. This competence relates to the development and management of the urban development projects pertaining to the implementation and integration of the compact, ecological, and technological dimensions of the landscape of data-driven smart sustainable cities of the future, including its spatial scaling, in line with the objectives and targets of sustainable development (Bibri and Krogistie 2021). One of the main functions of the office is undertaking what is called joined-up planning, a form of integration and coordination that enables the system-wide effects of environmental, economic, and social sustainability to be understood, analyzed, tracked, and built into the designs and responses characterizing the operations and functions of data-driven smart sustainable cities of the future thanks to urban intelligence and planning functions. These are envisaged for this new model of urbanism with regard to its designs, strategies, and policies in terms of development planning, which are in turn intended to shape and drive its operations and functions in terms of operative management.

Sustainable urban planning and design practices, including the spatial concretization of sustainability and the spatial scaling of urban form, are becoming highly responsive to a form of data-driven urbanism. One of the

consequences of data-driven urbanism is that the systems and domains of sustainable urban form are becoming much more tightly interlinked and coordinated respectively. This provides significant potential for enhancing the design strategies of sustainable urban form at different spatial scales, as well as how these can be implemented and amalgamated to increase the benefits of sustainability. Indeed, vast troves of urban data are being generated, analyzed, harnessed, and exploited to understand the complexity of sustainable cities, including their spatial scaling, so as to make their contribution to sustainability more measurable, tractable, and targeted for achieving better outcomes.

Besides, the field of sustainable urban form needs to extend its boundaries and broaden its horizons beyond the ambit of compact and ecological designs to include technological advances by unlocking and exploiting the synergistic, integrative, and substantive effects of data-driven technologies. Advanced technologies may overcome one of the scientific challenges pertaining to sustainable urban forms—relating their built infrastructure, urban infrastructure, economic infrastructure, and social infrastructure to their operational functioning and development planning through control, management, optimization, and enhancements. This will enable sustainable urban forms to leverage their collective intelligence in making actual progress towards integrating the dimensions of sustainability through new and innovative ways of generating designs and responses that improve sustainability.

4.2. Urban Forms and Spatial Scales as Processual Outcomes of Urbanization

Spatial scaling is of relevance and significance to the planning of data-driven smart sustainable cities of the future. Therefore, it needs to be more carefully addressed in this regard. In this light, it is important to understand how spatial scales should be conceived and implemented as part of the strategies of sustainable urban form. The conception of spatial scaling is predicated on the assumption that urban transformations, whether emergent or designed urban developments, represent outcomes of processes. For example, an urban fabric (e.g., inner city) created by multiple actor layers, incrementally developed with a diversity of building types, scales, and functions, is often seen as having the attributes of a more intense and livelier street lives (Eom and Cho 2015; Merlino 2011). However, like urban form, spatial scale is both the frame that shapes process and the frame that emerges from a process. Urban form may comprise different types of spatial scales, both of determined and undetermined types and extents. One of the key factors that shapes spatial scales as outcomes of processes is urbanization in terms of the processes of building, living, consuming, producing, and moving in and across the different areas of the city. Another key shaping factor relates to the emerging model of the city, and what this entails in terms of the ability of building advanced simulation models that respond to the city as an evolving and changing system and self-organizing social network embedded at different spatial scales.

Considering the above factors, spatial scales should be conceived as outcomes of complex processes.

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 reflecting the complexity of socio-economic and technical processes occurring in urban spaces, with no physical traces. This is in response to the current situation associated with the problematicity surrounding sustainable urban forms as quintessential complex systems in terms of their development planning and fragmentary design strategies and environmental technology solutions. This is compounded by urbanization and its negative consequences, as well as exacerbated by the unpredictability of climate change, economic crisis, pandemics, and demographic changes. This brings us to the issue of conceiving cities in terms of forms and pre-fixed scales 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.

Conceiving spatial scales in terms of fixed frames remains inadequate for understanding how the effects of sustainability are enacted at, between, across, and beyond different spatial scales as institutionalized units. This has a bearing on the efforts for increasing the sustainability aspects at different spatial scales. In fact, the emergence of real-time data from the bottom up is even causing space scales and time scales to collapse. In this respect, datasets are becoming able to show the real-time functioning of sustainable urban form, and also to imply how long-term changes can be detected and dealt with at different spatial scales and over different time scales thanks to the aggregation of real-time data. This is making it possible to advance the models that we are able to build and apply and the way in which they can inform the planning and decision processes with simulations and decision support conflated across space and time. Moreover, conceiving spatial scales in terms of outcomes of processes, supported by space-time convergence, is associated with the multi-scalar approach of sustainability effects as scalar outcomes. To make practical and effective use of this approach requires designing sustainable urban forms in

ways that allow to monitor, understand, analyze, and plan their spatial scaling to improve sustainability over different time scales. This will change the way sustainable urban forms can be planned across multiple spatial and time scales, raising the prospect of becoming smarter in the long term by continuous reflection in the short term.

4.3. An Integrated Approach to Multi-Scalar Outcomes and Spatial Scaling

Scale has been one of the key issues in the debate over sustainable urban forms. One urban form may involve one or a few institutionalized scales and less institutionalized scales. The approach that sees scales as outcomes of processes and actions performed in the lived environment implies that the effects of sustainability “are always enacted at different spatial scales in terms of size and dimension, and they are thus much more multi-scalar than suggested by the predefined scales of, for example, planning programmes and administrative organizations” (Kärrholm 2011, p. 98). With that in mind, although the environmental sustainability of a certain eco-district is prioritized in planning (see Bibri and Krogstie 2020a for Western Harbor and Royal Seaport in Sweden as illustrative examples), the environmental effects of the suggested plans are always multi-scalar, predicated on the entities, actors, or layers that make up the effects accounted for as environmentally sustainable. These entities are found at different levels or dimensions of complexity, and thus at different scales, including the municipality, the city, and the region. An important task would be to develop the administrative structures and planning instruments that enable the identification of the different spatial scales at which the suggested efforts for sustainability seem to be effective and have spatial impacts. This task can be facilitated by urban intelligence and planning functions, as discussed earlier.

Data-driven smart sustainable cities of the future involve the compact, ecological, and technological dimensions of sustainability that should be considered at multiple spatial scales. Still, new spatial scales may emerge as outcomes of processes, dominated by one or more of these dimensions, such as an eco-district, an eco-municipality, an eco-compact district, a data-driven smart eco-district, a compact inner-city, and a data-driven smart municipality, in addition to other less and non-institutionalized scales. Accordingly, data-driven smart sustainable cities of the future may be associated with the different kinds of sustainability effects that are also enacted at different spatial scales, including other spatial scales that may be loosely or completely integrated depending on their location in the city. In addition, to provide conditions that are conducive to integrating the three dimensions of sustainability as part of the planning of data-driven smart sustainable cities of the future at different spatial scales, it is important to amalgamate the different parts of the city spatially with the city center where all analytical and institutional centers are usually located. While taking into account the well-known prerequisites of sustainable urban design—a denser, well-integrated (spatially and socially) walkable, and greener city—as urban patterns to be monitored,

analyzed, and planned on the basis of urban computing and intelligence. Furthermore, underlying the multi-scalar approach is the idea of exploiting the integrative, constitutive, and pervasive nature of advanced ICT that enables connecting the various dimensions of the landscape of data-driven smart sustainable cities of the future as a way to leverage their collective intelligence with respect to computationally understanding urban life to enhance the different aspects of sustainability at different spatial scales by various means.

Scale is used as an analytical concept insofar as data-driven smart sustainable cities of the future are concerned with the different levels of the complexities of the components internally arranged to construct different wholes to produce the benefits of sustainability through advanced ICT. The outcomes of these complexities can be seen at different scales, and the differences in the underlying components can be found both in terms of size and category. Here the perspective on spatial scale differs from the scale analysis and scale theory (e.g., Collinge 2005; Marston et al. 2005; Smith 2003; Randles and Dicken 2004). In the context of this paper, spatial scale can be conceived of as materially concrete, digitally instrumented, and computationally augmented frames of socio-technical actions taking place over different temporal scales. This conception entails both the physical and technological aspects of the constructed whole resulting from the actions of people and processes of urban life. Spatial scale is also socio-culturally constructed and materially produced through institutional practices, supported and enhanced by data-driven technologies associated with urban computing and intelligence. Accordingly, it can be understood as a process that could relate to institutionalized, less institutionalized, and digitalized usages. The latter usage is particularly more sensitive to technological artefacts as one category of materialities, coupled with other categories (i.e., forms, shapes, and objects) as part of the physical characteristics making up the built-up area of any settlement. The technological artefacts as a key materiality are an indispensable co-producer of scale-related outcomes over different time scales. The other materialities, which concern compact and ecological designs of the built form, are indispensable co-producers of both scale and scale-related outcomes. This implies that scales are not always planned through policies. That is to say, scale is not always institutionally fixed, and scalar outcomes can be non-direct, unintentional (e.g., Randles and Dicken 2004), or generated as a result of urban data analytics as part of simulation models.

In addition, scale is regarded as dynamic and relational over different time spans, underpinned by the nature of the technologies embedded and used in space. This denotes the extent to which ICT is networked (e.g., the IoT sensor network) and the extensive interaction it enables across many domains and scales. So scale does not presume extent or size per se. Spatial scales as urban complexities are dynamically produced by different components, including urban actors, physical structures, technological artefacts, algorithmic rules and procedures, and so on. However, urban planning is mostly institutionalized

and diffused as a function of government (though with considerable public input in many Western societies). This in turn means that spatial scales are institutionalized as a certain predefined and predictable category of components. Once the spatial scale is fixed, its outcome becomes a matter of function determined by, among others, the materialities it entails, such as sizes, shapes, configurations, levels, and objects. Institutionalizing certain scales is a propensity of political regulations and spatial planning towards pre-determined administrative units (municipalities, counties, states/provinces, etc.).

4.4. Spatial Scale Amalgamation

This subsection presents the new ideas underlying the integration of the main spatial scales within the ambit of data-driven smart sustainable cities of the future as part of their development and design. The main focus is on the city, district, municipality, and neighborhood scales as complexities and predictable categories of the components producing the effects of environmental, economic, and social sustainability. The spatial scales encompass compact city strategies, eco-city strategies and technologies, data-driven smart city solutions, and environmentally data-driven smart sustainable city solutions in an integrated approach.

4.4.1. Integrating the District, the Municipality, and the City

While the eco-districts with their unique environmental profile can be planned to be heterogeneous and socially sustainable areas, it is still important to integrate them with the scale of the municipalities. A district is a type of administrative division that is managed by local government for specific purposes. An eco-district focuses on community collaboration, integrated communication, and cooperative management to help the city to be more successful in its environmental performance. Cooperative management tries to achieve more effective and equitable systems of resource management. In cooperative management, representatives of stakeholder groups, the scientific community, and local government agencies should share knowledge, power, and responsibility. A municipality is usually a single administrative division having corporate status and powers of self-government as granted by national and regional laws to which it is subordinate. In short, a municipality is a general-purpose administrative subdivision, as opposed to a special-purpose district. Accordingly, the assumption underlying the integration in question is that it is most likely to lead to positive no-direct and unintentional sub-scalar outcomes of sustainability through different processes and practices over time within the scale of the eco-district and in its relation to other spatial scales. In this regard, software-enabled technologies and urban data have become essential to the functioning of sustainable cities. Consequently, city operational governance and functioning are becoming highly responsive to a form of data-driven urbanism. However, to achieve the desired outcomes of the integration of the district and municipality scales, it is important to acknowledge that the urban is not confined to the administrative boundaries of

the new constructed whole; to consider local social-economic, cultural-political, and environmental contingencies in analyzing the development, implementation, and effects of development policies; and to socio-politically construct the urban problems to be solved by these policies and the considered solutions. Moreover, given their environmental status, the eco-districts studied tend to attract inhabitants of social homogeneity on the scale of the area, which in turn increases heterogeneity in terms of income on the scale of the municipality. This diversity can additionally contribute to social mix at the municipality level and thus reduce socio-economic and spatial segregation.

Furthermore, environmental, economic, and social aspects should be considered on both the scale of the eco-district and that of the city to avoid potential intra-territorial issues. In planning, a territory is of a certain size, and plans tend to focus on that territory and define the scale at which sustainability aspects are planned. Evaluations within the framework of data-driven smart sustainable cities of the future need to focus on the urban scale, not just the district or neighborhood scales in regard to sustainability. And the implementation of applied technology solutions should be systematically integrated in the management of the city.

While sustainable planning primarily seems to be an intra-territorial endeavor given the scattered nature of urban projects, the development and implementation of the ICT infrastructure together with the competencies needed to generate, transfer, and analyze urban data is, more often than not, planned for the whole city. Sustainability should be dealt with and solved within multiple scales rather than within the boundaries of one or a few territories and thus at one or a few scales. This is important to mitigate or avoid intra-territorial biases associated with responding to the environmental, economic, and social problems of sustainability. These are essentially integrated rather than specialized or sub-optimized. In addition, urban projects and initiatives should emphasize the connection between the different parts of the city with each other, and work on different spatial scales to enhance the local spaces of the city. These urban routes are important for spatial connections between the different parts of the city districts as well. For example, it is beneficial to integrate different modes of transport at the same place that allow connections to places located far away and close by via more complex network topologies for the purpose of generating multi-scalar outcomes of environmental, economic, and social sustainability. Places where the infrastructure of the neighborhood, the district, and the inner city mingle and meet (see Bibri and Krogstie 2020a for a practical initiative in an eco-district). While the notion of sustainability has triggered a new interest in the neighborhood as a unit for the city, conceptualizing neighborhoods as transit-oriented development (TODs) (Frey 1999; Jabareen 2006), the advent of advanced ICT has strengthened this conceptualization due to its ubiquitous and network nature, especially in relation to mobility. In fact, advanced ICT has dealt with the special conundrum pertaining to the physical-oriented conceptualization of

the neighborhoods. This is in the sense that the neighbourhood as a base for intervention is sometimes too large for questions such as safety, and too small for others such as integration and employment (see Bibri and Krogstie 2020a).

4.4.2. The Inner City as a Transformable or Evolvable Urban Fabric in Relation to the City Center

The focus here is on the inner city, a scale of a certain size. That is to say, a certain territory and thus a certain grain (Lynch 1990). One of the practical ideas that is worth considering in the planning of data-driven smart sustainable cities of the future is to design or redesign some parts of the inner city so that they can be transformed into a whole district developed for a specific purpose. This would depend on the location of the inner city. Otherwise, the inner city can simply be targeted by urban intensification projects as part of the expansion related to the compactness of the built form (i.e., higher density and adequate diversity together with mixed land uses) while relying on integrated (smart and sustainable) transport and energy systems and evenly distributed parks. In this respect, the inner city as an urban fabric can evolve into a sustainable urban form by multiple actors' interactions over time, with the idea to be spatially amalgamated with the city center and potentially other spatial scales. It is also of strategic value to plan and design some parts of the inner city from the start as a sustainable urban form in such a way that density, mixed land use, diversity, greening, and passive and low-energy houses/buildings are implemented as strategies by a number of developers simultaneously and continuously. The aim here is also to amalgamate the outcome with the city center and other spatial scales. In this case, all the three goals of sustainability should be supported and ideally balanced with the support of advanced technologies.

The focus on the inner city as an image follows the logic of postmodern urbanism (Ellin 1999). The pro-urban discourse of postmodern urbanism has been integrated into the discourse of sustainable urban form (Kärrholm 2011). As a way to de-problematize the issue of the inner city with its scale as a sub-model of the city for planning, the inner city should be open to be multifunctional in line with mixed use development. This design strategy is at the core of the compact city and the eco-city as central paradigms of sustainable urbanism (e.g., Bibri and Krogstie 2020a; Bibri, Krogstie, and Kärrholm 2020 for practical initiatives). This is in contrast to the inner city being an area of mono-functionality and consumption, as well as an anomaly with respect to its role as a live model for mixed uses (Kärrholm 2008). Modernist planning has focused on idealized plans developed top-down to deliver perfection at the moment of creation, based on control systems correcting "problems of yesterday" with a "conventional toolkit" (Taylor 2003, p. 157, cited in Batty and Marshall 2012). This planning approach has been criticized for creating simplified and rationalized urban forms out of diverse agendas, including reduced density and separation of urban functions (Alexander 1965; Marshall 2012).

4.4.3. Horizontal Approaches to Spatial Scales

A simple hierarchical structure can no longer function as a metaphor for data-driven smart sustainable cities of the future in terms of the spatial scales they entail. The underlying assumption is that this model of urbanism is overlaid by a digital skin that is used for storing, processing, and analyzing data for planning and governance purposes. Data-driven smart sustainable cities represent constellations of instruments across many spatial scales that are connected through multiple networks characterized by high speed and a modicum of intelligence. These networks provide 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 colossal amounts of data using the collective tools, processes, methods, techniques, and technologies that also transform the city into a data-driven enterprise. The generated data enable real-time analysis of urban life, as well as provides the raw material for envisioning and enacting more sustainable, efficient, resilient, equitable, and liveable urban environments. Digital instrumentation opens up dramatically different forms of the management of data-driven smart sustainable cities of the future. 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 in the context of sustainability.

Digital instrumentation is associated with what is called the horizontal information system for the city. Functionally compatible horizontal information systems allow the creation of an integrated ecosystem for the city. They serve to link together diverse smart technologies and solutions to coordinate the city systems and domains (Bibri 2020a; Kitchin 2016; Nikitin et al. 2016). Even urban operations centers and dashboards (Bibri and Krogstie 2020b, c; Kitchin 2014; Kitchin, Lauriault and McArdle 2015; Nikitin et al, 2016) are typically created to monitor the city holistically; 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 live service data for real-time decision-making and problem solving. One of the consequences of data-driven urbanism is that spatial scales, urban domains, and urban systems are becoming much more tightly interlinked. And also, vast troves of data are being generated, analyzed, harnessed, and exploited to understand the complex nature of sustainable urban forms and their spatial scaling so as to make them safer, more liveable, more equitable, and, above all, more efficient. In view of the above, data-driven urbanism is not by necessity a fully planned and regulated environment, responsive to change and any deviation from the rules that govern the form and function of the city.

Data-driven smart sustainable cities of the futures consist of a range of overlapping hierarchical, non-hierarchical, and horizontal structures. This is largely influenced by the way in which the ICT infrastructure underlying the functioning of the city system is planned, implemented,

and managed in regard to city operational management and development planning. With that in mind, it becomes relevant to establish different hierarchical structures, defining a multi-dimensional process of how to scale up and down and thereby avoiding the bias of a specific scale hierarchy that is determined by the concrete materiality of a set of frames of socio-technical actions.

Furthermore, the benefits of incorporating the horizontal components in the hierarchical structures are motivated by the complex nature of sustainability problems that need to be simultaneously addressed and overcome at different spatial scales. This may involve their physical amalgamation as the city evolves and grows in size and dimension as a result of urbanization. Urban development strategies include physical (land use change), geographical (population), economic (agglomeration), and societal (social and cultural change). These largely pertain to the design strategies of sustainable urban form, especially, compactness, density, multidimensional mixed-land use, and sustainable transportation. The outcomes of sustainability are best to be enacted across different spatial scales. A horizontal structure gives special importance to a focused approach based on multi-stockholder collaboration—a network in which a number of stakeholders come together in order to find a common approach to sustainability issues that affect them all and that is too complex to be addressed effectively without collaboration. This allows different stakeholders to focus and invest their energy and time on particular issues at each level of the scale hierarchy. The key stakeholders to be involved in this regard include: decision makers, policy makers, planners, developers, architects, experts, scientists, academics, scholars, professionals, business leaders, industrial engineering gurus, as well as civil society. Data-driven smart sustainable cities 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 advanced solutions for development planning in order to improve and advance sustainability beyond the spatial scaling of sustainable urban form. The sustainability efforts should result in positive environmental, economic, and social outcomes at multiple spatial scales at once based on the various frameworks of multi-stakeholder collaboration and cooperative management.

In addition, other spatial scales, which tend to be less institutionalized categories, could emerge to serve a particular purpose and respond to a particular need. Caniggia and Maffei (2001) point out a hierarchical change where de- and reterritorialization destabilize whole hierarchies of spatial institutionalizations. Sometimes, there is a need for some new areas to be territorialized as an urban category on a scale between the more established scales within the boundary of the city. Accordingly, some issues, activities, and forms formerly enacted on such scales could take place on the scale produced by new urban development projects, or by the modernization of the ICT infrastructure as part of the wide-scale instrumentation and datafication

of the city. New urban centers (innovation labs, research centers, operations centers, educational centers, etc.) could be established on new spatial scales affecting the whole field of urban establishments, or introducing new components to the existing urban fabrics. As such, they may destabilize previous structures and start the process of finding a new balance and hierarchic structure on other scales. Caniggia and Maffei (2001) and Alppi (2006) provide a detailed discussion on this topic in relation to business and retail. Such transformations assume a new approach to planning that does not always take pre-fixed spatial categories as its cue. Both urban and digital transformations affect the notions of predefined territories and hierarchies. The emerging data-driven approaches to planning may lead to a horizontal de- and restabilization of scales.

5. Conclusion

This paper analyzed and discussed the emerging conceptions of and approaches to spatial scales that should be considered in the planning of data-driven smart sustainable cities of the future. In doing so, it highlighted the innovative potential of urban computing and intelligence for enhancing and transforming the spatial scaling of sustainable urban form. The intractable issues engendered and special conundrums posed by urban growth exacerbate the wicked problems characterizing sustainable urban forms as quintessential complex systems, including those related to their spatial scaling from both design and technology perspectives with regard to planning. Besides, the experience of the past decades has shown that the conventional approaches to urban planning have been inadequate to cope with the adverse impacts of urbanization and rapid changes facing sustainable urban forms. Therefore, new circumstances require new responses concerning the planning of sustainable urban form and its spatial scaling. These responses are at the core of data-driven smart sustainable cities of the future. This academic discourse, which is constructed in light of new conceptions about the scientific, technological, environmental, economic, social, and institutional changes that took place in the past decade—contains an all-embracing understanding of the problems cities are facing and is also the defining context for suggested approaches and solutions as future possibilities for the problems and challenges of sustainability and urbanization.

Conceiving spatial scales as outcomes of processes rather than fixed frames and planning accordingly within the framework of data-driven smart sustainable cities of the future holds great potential for improving their contribution to the goals of sustainability. In addition, sustainability outcomes are of a multi-scalar nature, not solely bound to a particular spatial scale at which a certain sustainable urban form is implemented. This argument justifies the need to integrate spatial scales that have clear synergies in their management and planning and need to be coupled so to produce combined effects that are greater than the sum of their separate effects in respect of sustainability benefits. This form of integration can be enabled by urban computing and intelligence as

a set of technologies that bridge the gap between unobtrusive and ubiquitous sensing, intelligent computing, cooperative communication, and massive data management and analytics. This is to create novel solutions for sustainability by means of cloud and fog computing, the IoT, device to device (D2D) communication, data analytics techniques, Artificial Intelligence, simulation models, visual analytics methods, and decision support systems. One of the strengths of sustainability lies in its integrated approach to the problems that were previously specialized. This opens for a multi-scalar approach that does not conceive of spatial scales as institutionalized entities—but rather as a multitude of spatially enacted effects of sustainability. These are increasingly becoming measurable, knowable, and tractable thanks to the analytical power of big data on multiple urban domains, enabled by urban computing and intelligence. Data-driven smart sustainable cities of the future entail developing new models in various urban domains that pertain to the new kinds of data and movements and activities that are largely operated over multiple digital networks while concurrently relating these to traditional movements and locational activities.

Furthermore, when it comes to sustainability one cannot focus all the effort on a single and discrete space. Also, it is important to be more aware of the production of different scalar shifts from both urban and technological perspectives and the combination of these. Such shifts might be horizontal or vertical, minor or major, and homogenous or heterogenous. But since they are constantly at work, they need to be addressed more consciously. The fast-flowing torrent of urban data enables real-time analysis of urban systems across multiple spatial scales and over different time spans in regard to the operating and organizing processes of urban life, sophisticated approaches to interconnecting data across urban domains to provide detailed views of the relationships between urban data, and new modes of urban planning.

However, the uses of data-driven technologies come with perils and pitfalls. Bibri (2021b) provides a critical understanding of data-driven smart urbanism in terms of the associated risks and implications, raising several critical questions involving technocentric policies and technocratic governance, as well as other aspects of social sustainability. In addition to these concerns, smart urbanism remains selective, flawed, biased, normative, and politically inflected, although it purports to produce a commonsensical, neutral, apolitical, evidence-based form of urban planning and governance (e.g., Kitchin 2014, 2015, 2016; Luque-Ayala and Marvin 2015; Söderström, Paasche, and Klauser 2014). Furthermore, opening the notion of intelligence to contestation, Lynch and Del Casino (2020) examine differing conceptions of intelligence and what they might entail with regard to how to approach the theorization of “smart” spaces. The authors argue for a view of intelligence as multiple, partial, and situated in and in-between spaces, bodies, objects, and technologies, as well as call for attentiveness to the ways in which particular intelligences are prioritized over others, which may be suppressed and neglected, through the

production of smart spaces in the context of our rapidly changing understandings of the “humanness” of intelligence. All in all, while big data analytics and urban intelligence can bring numerous advantages to sustainable cities, it is equally important to acknowledge the fact that these advanced technologies can be problematic. Therefore, policymakers and planners should be careful when employing them.

Competing Interests

The author has no competing interests to declare.

Author Contribution

The author read and approved the published version of the manuscript.

References

- Alexander, C.** 1965. A city is not a tree. *Architectural Forum*, 122(1/2): 58–62.
- Alppi, S.** 2006. Where the flows freeze—Tracking the nodalities in the network city. Paper presented at Nordic and International Urban Morphology, Stockholm, Sweden, 3–5 September 2006.
- Batty, M, Axhausen, KW, Giannotti, F, Pozdnoukhov, A, Bazzani, A, Wachowicz, M, Ouzounis, G, Portugali, Y.** 2012. Smart cities of the future. *Eur Phys, J* 214: 481–518. DOI: <https://doi.org/10.1140/epjst/e2012-01703-3>
- Batty, M and Marshall, S.** 2012. The origins of complexity theory in cities and planning. In: Portugali, J, Meyer, H, Stolk, E and Tan, E (Eds.), *Complexity theories of cities have come of age*. Berlin, Germany: Springer Berlin Heidelberg. pp. 21–46. DOI: https://doi.org/10.1007/978-3-642-24544-2_3
- Bibri, SE.** 2020a. Advances in the Leading Paradigms of Urbanism and their Amalgamation: Compact Cities, Eco-cities, and Data-Driven Smart Cities, Springer, Berlin. DOI: <https://doi.org/10.1007/978-3-030-41746-8>
- Bibri, SE.** 2020b. The eco-city and its core environmental dimension of sustainability: green energy technologies and their integration with data-driven smart solutions. *Energy Inform*, 3: 4(2020). DOI: <https://doi.org/10.1186/s42162-020-00107-7>
- Bibri, SE.** 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*, 97: 1–20. DOI: <https://doi.org/10.1016/j.landusepol.2020.104703>
- Bibri, SE.** 2020d. A methodological framework for futures studies: integrating normative backcasting approaches and descriptive case study design for strategic data-driven smart sustainable city planning, 3: 31. DOI: <https://doi.org/10.1186/s42162-020-00133-5>
- Bibri, SE.** 2021a. Data-Driven Smart Sustainable Cities of the Future: Urban Computing and Intelligence for Strategic, Short-term, and Joined-up Planning, Computational Urban Science, (In Press).

- Bibri, SE.** 2021b. Data-Driven Smart Sustainable Cities of the Future: An Evidence Synthesis Approach to a Comprehensive State-of-the-Art Literature Review, Sustainable Futures. DOI: <https://doi.org/10.1016/j.sfr.2021.100047>
- Bibri, SE.** 2021c. 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. *Energy Inform*, 4: 4. DOI: <https://doi.org/10.1186/s42162-021-00138-8>
- Bibri, SE** and **Krogstie, J.** 2017. The core enabling technologies of big data analytics and context-aware computing for smart sustainable cities: a review and synthesis. *J Big Big Data*, 4(38): 1–50. DOI: <https://doi.org/10.1186/s40537-017-0091-6>
- Bibri, SE** and **Krogstie, J.** 2020a. Smart eco-city strategies and solutions for sustainability: the cases of royal seaport. Stockholm, Western Harbor, Malmö, Sweden. *Urban Sci*, 4(1): 1–42. DOI: <https://doi.org/10.3390/urbansci4010011>
- Bibri, SE** and **Krogstie, J.** 2020b. The emerging data-driven smart city and its innovative applied solutions for sustainability: the cases of London and Barcelona. *Energy Inform*, 3: 5. DOI: <https://doi.org/10.1186/s42162-020-00108-6>
- Bibri, SE** and **Krogstie, J.** 2020c. Environmentally data-driven smart sustainable cities: applied innovative solutions for energy efficiency, pollution reduction, and urban metabolism. *Energy Inf*, 3: 29. DOI: <https://doi.org/10.1186/s42162-020-00130-8>
- Bibri, SE** and **Krogstie, J.** 2021. 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 Environ*, 7(1): 3, 1–25. DOI: <https://doi.org/10.5334/fce.116>
- Bibri, SE, Krogstie, J** and **Kärholm, M.** 2020. Compact city planning and development: Emerging practices and strategies for achieving the goals of sustainability. *Developments in the built environment*, 4: 1–2. DOI: <https://doi.org/10.1016/j.dibe.2020.100021>
- Boudon, P.** 1999. The point of view of measurement in architectural conception: From the question of scale to scale as question. *Nordic Journal of Architectural Research*, 12(1): 7–18.
- Burton, E.** 2000. The compact city: just or just compact? A preliminary analysis. *Urban Stud.*, 37(11): 20. 1969. DOI: <https://doi.org/10.1080/00420980050162184>
- Burton, E.** 2002. Measuring urban compactness in UK towns and cities. *Environment and Planning B: Planning and Design*, 29: 219–250. DOI: <https://doi.org/10.1068/b2713>
- Campbell, S.** 1996. Green cities, growing cities, just cities? Urban planning and the contradictions of sustainable development. *Journal of the American Planning Association*, 62(3): 296–312. DOI: <https://doi.org/10.1080/01944369608975696>
- Caniggia, G** and **Maffei, GL.** 2001. Architectural composition and building typology, interpreting basic building. Firenze: Alinea.
- Collinge, C.** 2005. Flat ontology and the deconstruction of scale. *Transactions of the Institute of the British Geographers*, 31(2): 244–251. DOI: <https://doi.org/10.1111/j.1475-5661.2006.00201.x>
- Cugurullo, F.** 2016. Exposing smart cities and eco-cities: Frankenstein urbanism and the sustainability challenges of the experimental city. *Environ. Plan. A Econ. Space*, 50: 73–92. DOI: <https://doi.org/10.1177/0308518X17738535>
- Davoudi, S, Shaw, K, Haider, LJ, Quinlan, AE, Peterson, GD, Wilkinson, C,** et al. 2012. Resilience: A bridging concept or a dead end? 'Reframing' resilience: Challenges for planning theory and practice interacting traps: Resilience assessment of a pasture management system in Northern Afghanistan Urban Resilience: What does it mean in planning practice? Resilience as a useful concept for climate change adaptation? The politics of resilience for planning: A cautionary note. *Planning Theory & Practice*, 13(2): 299–333. DOI: <https://doi.org/10.1080/14649357.2012.677124>
- Dempsey, N.** 2010. Revisiting the compact city? *Built Environment*, 36(1): 5–8.
- Dempsey, N** and **Jenks, M.** 2010. The future of the compact city. *Built Environment*, 36(1): 116–121. DOI: <https://doi.org/10.2148/benv.36.1.116>
- Durack, R.** 2001. Village vices: The contradiction of new urbanism and sustainability. *Places*, 14(2): 64–69.
- Ellin, N.** 1999. Postmodern urbanism (New York, NY: Princeton Architectural Press).
- Eom, H-J** and **Cho, G-H.** 2015. Exploring thresholds of built environment characteristics for walkable communities: Empirical evidence from the Seoul metro-politan area. *Transportation Research Part D: Transport and Environment*, 40: 76–86. DOI: <https://doi.org/10.1016/j.trd.2015.07.005>
- Frey, H.** 1999. Designing the city: Towards a more sustainable urban form. London: E & FN Spon.
- Hofstad, H.** 2012. Compact city development: High ideals and emerging practices. *European Journal of Spatial Planning*, 1–23.
- Ihlebaek, C, Næss, P** and **Stefansdottir, H.** 2020. Are compact cities a threat to public health? *European Planning Studies* (IF 2.226). DOI: <https://doi.org/10.1080/09654313.2020.1775790>
- Jabareen, YR.** 2006. Sustainable urban forms: Their typologies, models, and concepts. *Journal of Planning Education and Research*, 26: 38–52. DOI: <https://doi.org/10.1177/0739456X05285119>
- Jenks, M, Burton, E** and **Williams, K.** 1996a. A sustainable future through the compact city? Urban intensification in the United Kingdom. *Environment by Design*, 1(1): 5–20.
- Jenks, M, Burton, E** and **Williams, K.** (Eds.) 1996b. The compact city: A sustainable urban form?. London: E & FN Spon Press.
- Jenks, M** and **Dempsey, N.** 2005. Future forms and design for sustainable cities. Oxford: Elsevier. DOI: <https://doi.org/10.4324/9780080455525>
- Jenks, M** and **Jones, C.** (Eds.) 2010. Dimensions of the sustainable city (Vol. 2). London: Springer.

- Joss, S.** 2010. Eco-cities—A global survey 2009. *WIT Transactions on Ecology and the Environment*, 129: 239–250. DOI: <https://doi.org/10.2495/SC100211>
- Joss, S.** 2011. Eco-cities: The mainstreaming of urban sustainability; key characteristics and driving factors. *International Journal of Sustainable Development and Planning*, 6(3): 268–285. DOI: <https://doi.org/10.2495/SDP-V6-N3-268-285>
- Kaido, K.** 2005. Urban densities, quality of life and local facility accessibility in principal Japanese cities. In: Jencks, M and Dempsey, N (Eds.), *Future Forms and Design for Sustainable Cities* (Oxford: Architectural Press). pp. 311–338.
- Kärrholm, M.** 2008. The territorialisation of a pedestrian precinct in Malmö: Materialities in the commercialisation of public space. *Urban Studies*, 9(45): 1903–1924. DOI: <https://doi.org/10.1177/0042098008093383>
- Kärrholm, M.** 2011. The scaling of sustainable urban form: Some scale—Related problems in the context of a Swedish urban landscape. *European Planning Studies*, 19(1): 97–112. DOI: <https://doi.org/10.1080/09654313.2011.530394>
- Kenworthy, JR.** 2006. The eco-city: Ten key transport and planning dimensions for sustainable city development. *Environ Urbaniz*, 18(1): 67–85. DOI: <https://doi.org/10.1177/0956247806063947>
- Kenworthy, JR.** 2019. Urban transport and eco—urbanism: a global comparative study of cities with a special focus on five larger Swedish urban regions MDPI: Urban Science. DOI: <https://doi.org/10.3390/urbansci3010025>
- Kitchin, R.** 2014. The real-time city? Big data and smart urbanism. *Geographical Journal*, 79: 1–14. DOI: <https://doi.org/10.1007/s10708-013-9516-8>
- Kitchin, R.** 2015. Data-driven, networked urbanism. The programmable city working paper, Maynooth University, County Kildare, Ireland. DOI: <https://doi.org/10.2139/ssrn.2641802>
- Kitchin, R.** 2016. The ethics of smart cities and urban science. *Philosophical Transactions of the Royal Society A*, 374: 1–15. DOI: <https://doi.org/10.1098/rsta.2016.0115>
- Kitchin, R, Lauriault, TP and McArdle, G.** 2015. Knowing and governing cities through urban indicators, city benchmarking & real-time dashboards. *Regional Studies in Marine Science*, 2: 1–28. DOI: <https://doi.org/10.1080/21681376.2014.983149>
- Lawson, B.** 2001. The language of space. Oxford: Architectural Press.
- Lim, HK and Kain, J-H.** 2016. Compact cities are complex, intense and diverse but: can we design such emergent urban properties? *Urban Plan*, 1(1): 95. DOI: <https://doi.org/10.17645/up.v1i1.535>
- Liu, W, Cui, P, Nurminen, JK and Wang, J.** 2017. Special issue on intelligent urban computing with big data. *Machine Vision and Applications*, 28: 675–677. DOI: <https://doi.org/10.1007/s00138-017-0877-8>
- Lozano, EE.** 1990. Community design and the culture of cities: The crossroad and the wall. Cambridge: Cambridge University Press.
- Lynch, K.** 1981. A theory of good city form. Cambridge, MA: MIT Press.
- Lynch, K.** 1990. Urban textures and networks. In: Banerjee, T and Southworth, M (Eds.), *City Sense and City Design, Writings and Projects of Kevin Lynch* (Cambridge, MA: MIT Press). pp. 261–276.
- Lynch, CR and Del Casino, VJ, Jr.** 2020. Smart spaces, information processing, and the question of intelligence. *Annals of the American Association of Geographers*, 110(2): 382–390. DOI: <https://doi.org/10.1080/24694452.2019.1617103>
- Marcotullio, PJ.** 2017. Towards Sustainable Cities: East Asian, North American and European Perspectives on Managing Urban Regions. Routledge, New York.
- Marshall, S.** 2012. Planning, design and the complexity of cities. In: Portugali, J, Meyer, H, Stolk, E and Tan, E (Eds.), *Complexity theories of cities have come of age*. Berlin, Heidelberg: Springer. pp. 191–206. DOI: https://doi.org/10.1007/978-3-642-24544-2_11
- Marston, S, Jones, JP, III and Woodward, K.** 2005. Human geography without scale. *Transactions of the Institute of British Geographers*, 31(2): 416–432. DOI: <https://doi.org/10.1111/j.1475-5661.2005.00180.x>
- Merlino, KR.** 2011. Urban grain and the vibrancy of older neighbourhoods: Metrics and measures. Considering research: Reflecting upon current themes in architectural research. Detroit, USA: Lawrence Tech University. pp. 477–488.
- Neuman, M.** 2005. The compact city fallacy. *Journal of Planning Education and Research*, 25: 11–26. DOI: <https://doi.org/10.1177/0739456X04270466>
- Nikitin, K, Lantsev, N, Nugae, A and 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>.
- Randles, S and Dicken, P.** 2004. ‘Scale’ and the instituted construction of the urban: Contrasting the cases of Manchester and Lyon. *Environment and Planning A*, 36(11): 2011–2032. DOI: <https://doi.org/10.1068/a3694>
- Register, R.** 1987. Ecocity Berkeley. Berkeley, CA: North Atlantic Books.
- Roseland, M.** 1997. Dimensions of the eco-city. *Cities*, 14(4): 197–202. DOI: [https://doi.org/10.1016/S0264-2751\(97\)00003-6](https://doi.org/10.1016/S0264-2751(97)00003-6)
- Smith, N.** 2003. Remaking scale: Competition and cooperation in pre-national and post-national Europe. In: Brenner, N, et al. (Eds.), *State/Space*. Oxford: Basil Blackwell. pp. 227–238. DOI: <https://doi.org/10.1002/9780470755686.ch13>
- Söderström, O, Paasche, T and Klausner, F.** 2014. Smart cities as corporate storytelling. *City*, 18: 307–320. DOI: <https://doi.org/10.1080/13604813.2014.906716>
- Taylor, P.** 2003. Time: From hegemonic change to everyday life. In: Holloway, S, Rice, S and Valentine, G (Eds.), *Key concepts in geography*, pp. 146–152.

- Williams, K.** 2010. Sustainable cities: Research and practice challenges. *International Journal of Urban Sustainable Development*, 1(1): 128–132. DOI: <https://doi.org/10.1080/19463131003654863>
- Williams, K, Burton, E and Jenks, M.** (Eds.) 2000. Achieving sustainable urban form. E & FN Spon, London.
- Yaneva, A.** 2005. Scaling up and down: Extraction trials in architectural design. *Social Studies of Science*, 35(6): 867–894. DOI: <https://doi.org/10.1177/0306312705053053>
- Yin, RK.** 2014. Case study research: Design and methods. Los Angeles, CA: Sage.
- Yin, RK.** 2017. Case study research and applications: design and methods (6th ed.). SAGE Publications, Inc.
- Zhang, JB, Zheng, Y and Qi, DK.** 2016. Deep spatio-temporal residual networks for citywide crowd flows prediction. In: *Proceedings of the 31st AAAI Conference on Artificial Intelligence*.
- Zheng, Y, Capra, L, Wolfson, O and Yang, H.** 2014. Urban computing: concepts, methodologies, and applications. *ACM Transactions on Intelligent Systems and Technology*, 5(3): 1–55, 222–235. DOI: <https://doi.org/10.1145/2629592>
- Zheng, Y, Yi, XW, Li, M, Li, RY, Shan, ZQ, Chang, E and Li, TR.** 2015. Forecasting fine-grained air quality based on big data. In: *Proceeding of the 21st SIG-KDD Conference on Knowledge Discovery and Data Mining (KDD 2015)*, 2267–2276. DOI: <https://doi.org/10.1145/2783258.2788573>

How to cite this article: Bibri, SE. 2021. Data-Driven Smart Sustainable Cities of the Future: New Conceptions of and Approaches to the Spatial Scaling of Urban Form. *Future Cities and Environment*, 7(1): 4, 1–15 DOI: <https://doi.org/10.5334/fce.120>

Submitted: 15 January 2021

Accepted: 15 April 2021

Published: 03 May 2021

Copyright: © 2021 The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC-BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. See <http://creativecommons.org/licenses/by/4.0/>.

]u[*Future Cities and Environment*, is a peer-reviewed open access journal published by Ubiquity Press.

OPEN ACCESS 