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Compact urbanism and the synergic potential of its integration with data-driven smart urbanism : An extensive interdisciplinary literature review

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ABSTRACT

Sustainable cities have, since the early 1990s, been the leading global paradigm of urbanism thanks to the different models of sustainable urban form proposed as new frameworks for the redesigning and restructuring of urban places to make urban living more sustainable. The compact city is the most preferred model of sustainable urbanism for responding to the challenges of sustainable development. However, despite the benefits claimed by the advocates of this model, its critics highlight a number of conflicts and contentions. This is coupled with several problems, issues, and challenges considering the very fragmented picture that arises of change on the ground in the face of urbanization. In this context, it has been suggested that the compact city needs to embrace and leverage what advanced ICT has to offer so as to improve, advance, and maintain its contribution to sustainability. With the above in regard, this paper provides a comprehensive state–of–the–art review of compact urbanism as a set of planning and development practices and strategies, focusing on the three dimensions of sustainability and the significant, yet untapped, potential of big data technology for enhancing such practices and strategies under what is labelled 'data–driven smart sustainable urbanism.' This paper identifies compactness, density, diversity, mixed land use, sustainable transportation, and green space as the prevalent design strategies of the compact city. At the heart of this model is the clear synergy between the underlying strategies in terms of their cooperation to produce combined effects greater than the sum of their separate effects as regards the tripartite value of sustainability. Indeed, this paper corroborates that the compact city is justified by its ability to contribute to the environmental, economic, and social goals of sustainability. Nevertheless, the economic goals seem to dominate over the environmental and social goals, notwithstanding the general claim about the three sustainability dimensions being equally important and mutually dependent. Further, this paper reveals that big data technology holds great potential for enhancing compact urbanism with respect to sustainability. This thorough review of and critique on the existing work on the compact city provides a reference for researchers and practitioners in related communities and the necessary material to inform these communities of the latest developments in the field of compact urbanism and its relation to data–driven smart urbanism. This work serves to inform various urban stakeholders about the benefits of data-driven smart solutions for advancing sustainability.

1. Introduction

Cities have a defining role in strategic sustainable development. Therefore, they have gained a central position in operationalizing this notion and applying this discourse. This is clearly reflected in the Sustainable Development Goal 11 (SGD 11) of the United Nations' 2030 Agenda, which entails making cities more sustainable, resilient, inclusive, and safe (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 ICT has been under investigation by the UN (2015c) through their study on 'Big Data and the 2030 Agenda for Sustainable Development.'

Sustainable cities, an umbrella concept for various models of sustainable urban forms, have been the leading global paradigm of urbanism (e.g., Bibri, 2019a; Jabareen, 2006; Van Bueren et al., 2011; Wheeler and Beatley, 2010; Whitehead, 2003; Williams, 2010) for over

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three decades. Indeed, significant advances in some areas of sustainability knowledge and a multitude of exemplary practical initiatives have been realized, thereby raising the profile of sustainable cities. The subject of 'sustainable cities' remains endlessly fascinating and enticing, as there are numerous actors involved in the academic and practical aspects of the endeavor, including engineers and architects, green technologists, built and natural environment specialists, and environmental and social scientists, and, more recently, ICT experts, data scientists, and urban scientists (Bibri, 2019a). All these actors are undertaking research and developing strategies to tackle the challenging elements of sustainable urbanism. In addition to this is the work of policymakers and political decision–makers in terms of formulating and implementing regulatory policies and devising and applying political mechanisms and governance arrangements to promote and spur innovation and monitor and maintain progress in sustainable cities, especially compact cities. A number of recent UN–Habitat reports and policy documents argue that the compact city model has positive effects on resource efficiency, economy, citizen health, social cohesion, and cultural dynamics (UN Habitat, 2011, 2014a, 2014c, 2015)

In the early 1990s, the discourse on sustainable development produced the notion of compact city planning and development that became a hegemonic response to the challenges of sustainable development (Jenks and Dempsey, 2005) by focusing on intensification, creating limits to urban growth, encouraging mixed–use and diverse development, and placing a greater focus on the role of public transportation and quality of urban design (Arbury, 2005). In the EU Green Paper of the Urban Environment, the compact city model was advocated as the most sustainable for urban development (CEC, 1990). Indeed, according to many studies (e.g., Bibri, 2020; Bibri and Krogstie, 2017b; Jabareen, 2006; Næss et al., 2011a,b; Newman and Kenworthy, 1999), the compact city can promote sustainability by reducing the amount of travel and shortening commute time; decreasing car dependency; lowering per capita rates of energy use; limiting the consumption of building and infrastructure materials; mitigating pollution; maintaining the diversity for choice among workplaces, service facilities, and social contacts; and limiting the loss of green and natural areas. Cities can harness the advantages of agglomeration and tap into the variety of benefits that compact cities have to offer through proper planning, development, and governance. In particular, cities as the most compact settlements of people have a tremendous effect on environmental changes (Girardet and Schumacher, 1999), and low population density is the most environmentally harmful form in urban structures (UN Habitat, 2014b).

However, the benefits of compact cities are not guaranteed as desired outcomes. This relates to the issues argued against by the critics of the compact city model that should be addressed so that it can gain in more popularity. By and large, most of these issues pertain to the unforeseen consequences and unanticipated effects of compact cities that fall under what is called in urban planning 'wicked problems', a term that has gained more currency in urban policy analysis after the adoption of sustainable development within urban planning since the early 1990s. And that are often overlooked because of failing to approach compact cities from a holistic approach, or to treat them in too immediate and simplistic terms. Rittel and Webber (1973), the first to define the term, associate wicked problems with urban planning, arguing that the essential character of wicked problems is that they cannot be solved in practice by a central planner. Such problems are so complex and dependent on so many factors that it is hard to grasp what exactly the problem is, or how to tackle it. In other words, they are difficult to explain and impossible to solve because of the incomplete, contradictory, and changing requirements that are not easy to recognize.

In addition, in the current climate of the unprecedented urbanization and increased uncertainty of the world, it may be more challenging for cities in developed countries to configure themselves sustainably. The predicted 70 % rate of urbanization by 2050 (UN, 2015d) reveals that the sustainability of the urban environment will be a key factor in the global resilience to the forthcoming changes. This implies that the city governments across the globe will face significant challenges pertaining to environmental, economic, and social sustainability due to the issues engendered by urban growth. These include increased energy consumption, pollution, toxic waste disposal, resource depletion, inefficient management of urban infrastructures and facilities, inadequate planning processes and decision–making systems, poor housing and working conditions, saturated transport networks, endemic congestion, and social inequality and vulnerability (Bibri, 2019a, 2020), In a nutshell, urban growth raises a variety of problems that tend to jeopardize the sustainability of cities, as it puts an enormous strain on urban systems and processes as well as ecosystem services.

Against the backdrop of the escalating rate and scale of urbanization and the mounting challenges of sustainability, a number of alternative ways of planning, designing, managing, and governing cities based on advanced ICT have materialized and are rapidly evolving, providing the raw material for how sustainable urban forms can improve, advance, and maintain their contribution to the goals of sustainable development (Bibri, 2018b, 2019a, b, c; Bibri and Krogstie, 2017c), as well as for how smart cities can transition towards the needed sustainable development (e.g., Al Nuaimi et al., 2015; Batty et al., 2012). These two main urbanism approaches: sustainable cities and smart cities have been developing for quite some time: since the diffusion of sustainable development around the early 1990s and the prevalence of ICT around the mid1990s respectively. But what is new is that the emerging urban initiatives and endeavors are shifting from merely focusing on the application of sustainability knowledge to city planning and design or the development and deployment of smart technologies to optimize these practices to integrating the sustainable city and the smart city as both landscapes and approaches (Bibri, 2019f).

There is an increasing recognition that advanced ICT constitutes a promising response to the challenges of sustainable development in the face of urbanization due to its tremendous, yet untapped, potential for solving many socio–economic and environmental problems (see, e.g., Angelidou et al., 2017; Batty et al., 2012; Bibri and Krogstie, 2017a, 2019a, b; Höjer and Wangel, 2015; Kotharkar et al., 2014). Therefore, advanced ICT has recently come to the fore and become of fundamental importance as to mitigating the negative effects of urbanization and tackling the conundrums of sustainability. Many urban development approaches emphasize the role of big data technologies and their novel applications as an advanced form of ICT in advancing sustainability (e.g., Al Nuaimi et al., 2015; Batty et al., 2012; Bettencourt, 2014; Bibri, 2018b, 2019a, b, c, f; Pantelis and Aija, 2013). Indeed, there has recently been a conscious push for cities across the globe to be smarter and more sustainable by developing and implementing big data technologies and their novel applications in relation to various urban domains to enhance and optimize urban designs, strategies, policies, operations, functions, and services.

A large body of work has investigated the presumed outcome of the compact city model achieved through planning practices and development strategies. More specifically, scholars have discussed to what extent this model of sustainable urban form produce the claimed environmental, economic, and social benefits of sustainability (Jenks and Jones, 2010; Lin and Yang, 2006; Burton, 2002). Here the focus is often on the design strategies underlying the compact city model (Bibri and Krogstie, 2017b; Boussauw et al., 2012; Dumreicher et al., 2000; Jabareen, 2006; Kärrholm, 2011; Van Bueren et al., 2011; Williams et al., 2000). This line of research directs attention to their link to the goals of sustainable development. A recent wave of research has moreover started to focus on integrating these design strategies with advanced ICT, especially big data technology and its novel applications, to improve the contribution of sustainable urban forms to sustainability (e.g., Bibri, 2018b, 2019a; Bibri and Krogstie, 2017b, 2019a, b). This wave of research opens the way for cross–domain analyses in terms of integrating physical, spatial, environmental, economic, social, technological, and scientific aspects. This paper follows this path by providing a comprehensive state–of–the–art review of the compact city as a set of planning and development practices and strategies, focusing on the three dimensions of sustainability and the significant, yet untapped, potential of big data technology for enhancing such practices and strategies under what is labelled 'data–driven smart sustainable urbanism.' Specifically, it seeks to answer the following questions:

1 What are the prevalent design principles and strategies of the compact city model, and in what ways do they mutually complement and beneficially affect one another?
2 What kind of conflicts and contentions does the compact city model raise, and how can they be explained?
3 To what extent does the compact city model contribute to the environmental, economic, and social goals of sustainable development?
4 What kind of problems, issues, and challenges do pertain to the compact city, and what is the potential and role of big data technology for solving or mitigating them?

In doing so, it endeavors to deliver a detailed analysis, critical evaluation, and well-worked discussion of the available qualitative and quantitative research covering the topic of compact cities and the broader field within which it falls: sustainable urbanism, including its smart data-driven dimension. In this regard, the added value of this work lies in its comprehensiveness, thoroughness, topicality, and original contribution in the form of new insights as a result of synthesizing a large body of interdisciplinary works on the leading paradigms of urbanism: sustainable cities and data-driven smart cities. The latter pertains to the role of big data technology and its novel applications in enhancing and optimizing urban operations, functions, designs, strategies, and policies beyond the ambit of the built form.

This paper unfolds as follows. Section 2 outlines the literature review methodology in terms of category, search strategy, selection criteria, organizational approach, and purpose. In Section 3, the relevant conceptual, theoretical, and discursive foundations are introduced, described, and integrated. Section 4 provides a thorough analysis, evaluation, and discussion of the phenomenon of the compact city as a leading paradigm of sustainable urbanism and its relation to data–-driven smart urbanism. Finally, this paper concludes, in Section 5, by summerizing the key findings, providing some reflections, highlighting the key contributions, and suggesting some future research avenues.

2. Literature review methodology: a topical approach

This interdisciplinary review involves the exploration of a vast and diverse array of literature on the topic (including journal articles, conference proceedings, books, reports, and dissertations) of compact cities, integrating various disciplinary fields while putting an emphasis on the qualitative research in the field. Interdisciplinarity has become a widespread mantra for research within diverse fields, accompanied by a growing body of academic publications. The field of sustainable urban forms is profoundly interdisciplinary in nature, so too is the research within, and thus literature on, it. This scholarly perspective also applies to any review of this literature in the sense of using insights and methods from several disciplines. These include, but are not limited to: urban planning and development, sustainable development, science and technology, geography, ecology, environmental science, economics, and policy and politics. Accordingly, this interdisciplinary literature review is a topical, analytical, and organizational unit that is justified by the nature and orientation of the research field of sustainable urban forms. Adopting a topical approach to this review is thus deemed more relevant than a systematic one, and this paper determines the usefulness of this substantive category of review.

A review method was developed as a means to indicate the issues to be addressed, search strategy for retrieving the sought articles and other documents, inclusion and exclusion criteria for identifying and selecting the relevant ones, and abstract review protocols.

2.1. Hierarchical search strategy and scholarly sources

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

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

In addition, the collection process is based on Scott's (1990) four criteria for assessing the quality of the sought material, namely:

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

2.2. Selection criteria: inclusion and exclusion

To find out what has already been written on the topic of compact cities, the above search approach was adopted with the objective to identify the relevant studies addressing the diverse research strands that cover the questions this paper intends to answer in relevance to the empirical study to be conducted. Therefore, the preliminary selection of the available material was done in accordance to the problems under investigation, using a variety of sources. This is underpinned by the recognition that once the research problems are set, it becomes possible to refine and narrow down the scope of reading, although there may seem to be a number of sources of information that appear pertinent. With that in mind, for a document to be considered in terms of its ability to provide any information of pertinence, it should pertain to one of the conceptual/theoretical subjects and thematic/topical categories specified in accordance with the questions to be answered as representing in this context the headings of the sections and subsections of this paper. The focus was on the documents that provided definitive primary information typically from a cross-domain analysis perspective. While certain methodological guidelines were deemed essential to ensure the validity of the review, it was of equal importance to allow flexibility in the application of the topical literature review approach to capture the essence of the research within the interdisciplinary field of sustainable urban forms, with a focus on compact cities. The whole idea was to 'accumulate a relatively complete census of relevant literature' (Webster and Watson, 2002, p. 16). On the whole, scoring the documents was based on the inclusion of issues related to the topic on focus. Conversely, the documents excluded were those that did not meet the specific criteria in terms of their relevance to the questions being addressed. As to abstract review, the abstracts were reviewed to assess their pertinence to the review and to ensure a reliable application of the inclusion and exclusion criteria. Inclusionary discrepancies were resolved by the re–review of abstracts. The process allowed to further refine and narrow down the scope of reading.

The keywords searched included 'compact city','compact urban form','sustainable urban form','sustainable urban planning','sustainable cities','compact city planning','compact city development','compact city design','compact city policy','compact city dimensions','sustainable

Table 1
Dimensions of the built environment.
Source: Handy et al. (2002).

Dimension	Definition	Exemples
Density and intensity	Amount of activity in a given area	Persons per acre or jobs per square mile Ratio of commercial floor space to land area
Land use mix	Promixity of different land uses	Distance from house to nearest store Share of total land area for different uses Dissimilarity index
Street connectivity	Directness and availability of alternative routes through the network	Intersections per square mile of area Ratio of straight–line distance of network distance Average block length
Street scale	Three–dimensional space along a street as bounded by buildings	Ratio of building heights to street width Average distance from street to buildings
Aesthetic quality	Attractiveness and appeal of a place	Percent of ground in shade at noon Number of locations with graffiti per square mile
Regional structures	Distribution of activities and transportation facilities across the region	Rate of decline in density with distance from downtown Classification based on concentrations of activity and transportation network

urban development','urban intensification','urban densification','compactness','urban density','mixed use development','land use and sustainable transportation','sustainable built environment', 'sustainable development AND urban form', 'sustainable cities AND big data technology', 'sustainable urban forms AND big data technology','sustainable urban development AND big data technology', 'smart sustainable cities AND big data applications', 'urban planning AND big data analytics AND sustainable development','data–driven smart sustainable urbanism', and 'data–driven smart urbanism AND sustainable development', in addition to some derivatives of these keywords. These were used to search against such categories as the documents' keywords, title, and abstract to produce some initial insights into the topic. To note, due to the limitations associated with relying on the keyword approach, backward literature search (backward authors, backward references, and previously used keywords) and forward literature search (forward authors and forward references) were additionally used to enhance the search approach (Webster and Watson, 2002).

2.3. Purpose

The literature review is typically performed to serve many different purposes. This depends on whether or not it is motivated by, or an integral part of, a research study, as well as on its focus and scope. However, considering the aim of this paper and its relation to the empirical study to be conducted, this review was carried out with the following specific purposes in mind:

- To examine and discuss the underlying foundational constructs and their integration from an interdisciplinary perspective.
- To analyse, evaluate, and synthesize the existing knowledge in line with such constructs set for the empirical study to be conducted.
- To highlight the strengths, weaknesses, omissions, and contradictions of the existing knowledge, thereby providing a critique of the research that has been done within the field.
- To discuss the identified strengths and weaknesses with respect to the environmental, economic, and social goals of sustainability and the extent to which they are balanced.
- To identify the knowledge gaps and research opportunities within the field.
- To identify the key relationships between the findings of the relevant studies addressing the different strands of the topic on focus by comparing them and linking their results.

3. Conceptual, theoretical, and discursive foundations

3.1. The built environment

The built environment refers to the human–made surroundings that provide the setting for human activity and what this entails in terms of land use, transport systems, and the spatial patterns of physical objects and their design features. It encompasses urban places and spaces created, restructured, and redesigned by people, including buildings, green infrastructure, and public infrastructure. The built environment is at the core of sustainable urban forms in the sense that the latter has emerged to enable the former to function in a sustainably constructive way, e.g., to environmentally contribute beneficially to the planet for the present and future generations in terms of reducing material use, lowering energy consumption, mitigating pollution, and minimizing waste. However, the built environment has been referred to by a variety of terms, which tend to be used interchangeably. Handy et al. (2002) describe it as an amalgam of land use, urban design, and the transportation system, including patterns of human activity and mobility within the physical environment. Roof and Oleru (2008) define it as the human–made space in which people live, work, and recreate on a day–to–day basis. Past studies within urbanism have typically focused on different spatial levels of the built environment, including the neighborhood, district, city, and regional scales. For example, Handy et al. (2002) discuss measures of the built environment by categorizing them into neighborhood and regional features, with at least five interrelated and often correlated dimensions of the built environment at the neighborhood scale, as suggested by several studies (Table 1).

3.2. Sustainable urban planning, design, and development

Urban planning is concerned with the development and design of land use and the built environment. As a governmental function in most countries, it is practiced on neighborhood, district, municipality, city, metropolitan, regional, and national scales, with land use, environmental, transport, and local planning representing more specialized *foci*. It has been approached from a variety of perspectives, often combined, including physical, spatial, geographical, ecological, technical, economic, social, cultural, and political. As an interdisciplinary field, it involves transportation planning, environmental planning, land–use planning, policy recommendations, and public administration, as well as strategic thinking, sustainable development, landscape architecture, civil engineering, and urban design (Nigel, 2007). Urban planning is associated with different kinds of urban systems, namely (Bibri, 2019a):

- Built form (buildings, streets and boulevards, neighborhoods, districts, residential and commercial areas, schools, parks, public spaces, etc.).
- Urban infrastructure (transport systems, water and gas provision systems, sewage systems, power distribution systems, etc.).
- Human services (public services, social services, cultural facilities, recreational and green spaces, etc.).
- Administration (management, governance, policy, regulatory frameworks, practices, policy design and recommendation, technical and assessment studies, etc.).

Sustainable urban planning is the process of guiding and directing the development and design of land, urban environment, urban infrastructure, and related processes, activities, and services in ways that contribute to sustainable development towards achieving sustainability. As such, it involves defining the long–term goals of sustainability; formulating sustainable development objectives to achieve such goals; arranging the means and resources required for attaining such objectives; and implementing, monitoring, steering, evaluating, and improving all the necessary steps in their proper sequence towards reaching the overall aim.

Urban design is an integral part of urban planning. It is concerned with planning, landscape architecture, and civil engineering, as well as sustainable urbanism, ecological urbanism, sustainable design, ecological design, and strategic design (Bibri and Krogstie, 2017a). Dealing with the design and management of the public domain and the way this domain is experienced and used by urbanites, urban design refers to the process of designing, shaping, arranging, and reorganizing urban physical structures and spatial patterns. As to its sustainable dimension, it is aimed at making urban living more environmentally sustainable and urban areas more attractive and functional (e.g., Aseem, 2013; Boeing et al., 2014; Larice and MacDonald, 2007). In this respect, urban design is about making connections between forms for human settlements and environmental and social sustainability, built environment and ecosystems, people and the natural environment, economic viability and well–being, and movement and urban form.

Urban development refers to urbanization with its different dimensions, especially physical (land use change), geographical (population), societal (social and cultural change), and economic (agglomeration). Urban planning as a technical and political process is seen as a valuable force to achieve sustainable development through design, among other things. Sustainable urban development can be viewed as an alternative approach to urban thinking and practice. It focuses primarily on addressing and overcoming the escalating environmental problems and the rising socio–economic issues associated with the predominant paradigm of urban development by mitigating or eliminating its negative impacts on the environment and improving human well–being. In short, sustainable urban development is a strategic approach to achieving the long–term goals of sustainability. As such, it requires that scholars, practitioners, organizations, institutions, and governments agree upon concrete ways to determine the most effective approaches and strategic actions in a concerted effort to reach a sustainable future.

3.3. Sustainable cities

There are multiple views on what a sustainable city should be or look like and thus various ways of conceptualizing it. Generally, a sustainable city can be understood as a set of approaches into operationalizing sustainable development in, or practically applying the knowledge about sustainability and related technologies to the planning and design of existing and new cities or districts. It represents an instance of sustainable urban development, a strategic approach to achieving the long–term goals of urban sustainability. Accordingly, it needs to balance between the environmental, economic, and social goals of sustainability as an integrated process. Specifically, as succinctly put by Bibri and Krogstie (2017a, p. 11), a sustainable city 'strives to maximize the efficiency of energy and material use, create a zero–waste system, support renewable energy production and consumption, promote carbon–neutrality and reduce pollution, decrease transport needs and encourage walking and cycling, provide efficient and sustainable transport, preserve ecosystems and green space, emphasize design scalability and spatial proximity, and promote livability and community–oriented human environments.'

3.4. Sustainable urban forms

There are different instances of sustainable cities, which are identified as models of sustainable urban forms, including compact cities, eco–cities, green cities, new urbanism, landscape urbanism, and urban containment. Of these, compact cities are advocated as the most sustainable and environmentally sound model. Lynch (1981, p. 47) defines urban form as 'the spatial pattern of the large, inert, permanent physical objects in a city.' Specifically, urban form represents aggregations of repetitive elements as integrated characteristics pertaining to land use patterns, spatial organizations, and other urban design features, as well as transportation systems and environmental and urban management systems (Handy, 1996; Williams et al., 2000). In other words, urban form results from bringing together many urban patterns, which 'are made up largely of a limited number of relatively undifferentiated types of elements that repeat and combine' (Jabareen, 2006, p. 39). In concrete terms, the spatial pattern entails similarities and grouped conceptual categories (Lozano, 1990) that comprise such components as building densities, block sizes and shapes, street designs, area configurations, spatial scales, public space arrangements, and park layouts (Jabareen, 2006). In Achieving Sustainable Urban Form, Williams et, al. (2000, p. 355) conclude that sustainable urban forms are 'characterized by compactness (in various forms), mix of uses and interconnected street layouts, supported by strong public transport networks, environmental controls and high standards of urban management'.

Sustainable development has, since its widespread diffusion in the early 1990s, significantly influenced urban planning and development. As a result of reviving the discussion about the form of cities and giving a major stimulus to the question of the contribution that certain urban forms might make to sustainability (Jabareen, 2006), it has undoubtedly inspired a whole generation of urban scholars and practitioners into a quest for the immense opportunities and fascinating possibilities that could be explored by, and the enormous benefits that could be realized from, the planning and development of sustainable urban forms (Bibri, 2018a). That is to say, forms for human settlements that will meet the requirements of sustainability and enable the built environment to function in ways that enhance and optimize urban systems in line with the goals of sustainable development in terms of reducing material use, lowering energy consumption, mitigating pollution, and minimizing waste, as well as improving social equity, the quality of life, and well–being. The term "smart sustainable urban form" can be defined as a form for human settlements with all these characteristic features supported with the instrumentation, datafication, and computational analysis of the built environment on the basis of big data technologies and their applications. The latter serve to monitor, understand, analyze, plan, and design the city and to enhance and optimize its operations, functions, and services in line with the goals of sustainable development.

3.5. Smart sustainable urbanism: a data-driven approach

Smart sustainable cities relies on constellations of instruments across many scales that are connected through multiple networks augmented with intelligence, which provide and coordinate continuous data regarding the different aspects of urbanity in terms of the flow of decisions about the physical, environmental, social, and economic forms of the city. The evolving research and practice in the field of smart sustainable urbanism tends to focus on harnessing and exploiting the ever–increasing deluge of the data that flood from urban systems and domains by using and leveraging the value extracted from this deluge through analytics in enhancing decision making pertaining to sustainability. Urban systems include built form, urban infrastructure, ecosystem services, human services, and administration and governance. Urban domains involve transport, traffic, mobility, energy, natural environment, land use, healthcare, education, science and innovation, and public safety. Accordingly, urban systems and domains, which overlap in many aspects, span the physical, environmental, social, and economic dimensions of sustainability.

Furthermore, smart sustainable urbanism entails developing urban intelligence functions as an advanced form of decision support on the basis of the useful knowledge that is extracted from large masses of data. Urban intelligence functions represent new conceptions of how smart sustainable cities function and utilize and combine complexity science, urban science, and data science in fashioning powerful new forms of urban simulations models and optimization and prediction methods that can generate urban structures and forms that improve sustainability, efficiency, resilience, and the quality of life (Bibri, 2019a, c). In a nutshell, data–driven solutions are of paramount importance to the practice of smart sustainable urbanism in the light of the escalating urbanization. In this field, the operation and organization of urban systems and the coordination of urban domains require not only the use of complex interdisciplinary knowledge, but also the application of advanced technologies, sophisticated approaches, and powerful computational analytics (Batty et al., 2012; Bibri, 2019a; Bibri and Krogstie, 2018; Bibri et al., 2020; Bettencourt, 2014). In their comprehensive survey on data–driven smart cities, Nikitin et al. (2016) point out that modern cities employ the latest technologies to support sustainable development given rapid urban growth, increasing urban domains, and more complex infrastructure.

The technical features of sustainable urbanism entails the application of advanced ICT as a set of scientific and computational approaches and technical processes. Recent evidence (e.g., Al Nuaimi et al., 2015; Angelidou et al., 2017; Batty et al., 2012; Bettencourt, 2014; Bibri, 2018a, b, 2019a, c, Bibri and Krogstie, 2017b) lends itself to the argument that an integration of the components of sustainable urbanism (i.e., natural ecosystems, physical structures, urban forms, spatial organizations, natural resources, urban infrastructures, socio–economic networks, and ecosystem and human services) with cutting–edge big data technologies can create more sustainable, resilient, livable, and equitable cities. Achieving the goals of urban sustainability through sustainable urban development as a strategic process entails continuously unlocking and exploiting the untapped potential and transformational power of advanced ICT given its disruptive, substantive, and synergetic effects on the forms and practices of sustainable urbanism in the high of the expanding urbanization. Townsend (2013) portrays urban growth and ICT advancement as a form of symbiosis.

One area of advanced ICT that has recently gained increased attention and prevalence is big data analytics. This emerging paradigm of computing combines large–scale computation, new data–intensive techniques and algorithms, and advanced mathematical models to build and perform data analytics. Accordingly, big data computing demands a huge storage and computing power for data curation and processing for the purpose of extracting the useful knowledge intended more than often for immediate use in decision–making processes. It generally includes: advanced techniques based on data science fundamental concepts and computer science methods, data mining models, computational mechanisms involving sophisticated and dedicated software applications and database management system, advanced data mining tasks and algorithms, simulation models, prediction and optimization methods, data processing platforms, and cloud and fog computing models.

3.6. Big data computing and the underpinning technologies

Big data computing is an emerging paradigm of data science, which is of multidimensional data mining for scientific discovery over–large scale infrastructure. Data mining/knowledge discovery and decision––making from voluminous, varied, real–time, exhaustive, fine–grained, indexical, dynamic, flexible, evolvable, relational data is a daunting challenge/task in terms of storage, management, organization, processing, analysis, interpretation, evaluation, modeling, and simulation, as well as in terms of the visualization and deployment of the obtained results for different purposes. Big data computing amalgamates, as underpinning technologies, large–scale computation, new data–intensive techniques and algorithms, and advanced mathematical models to build and perform data analytics. Accordingly, big data computing demands a huge storage and computing power for data curation and processing for the purpose of discovering new or extracting useful knowledge typically intended for immediate use in an array of multitudinous decision–making processes to achieve different purposes. It entails the following components (see Bibri, 2019a; for a detailed descriptive account):

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

There is no agreed academic or industry definition of big data. Therefore, many definitions have been suggested and are available in the literature, with each tending to offer a particular or different view of the concept based on the context of use. Generally, the term 'big data' is essentially used to mean collections of datasets whose volume, velocity, variety, exhaustivity, relationality, and flexibility make it so difficult to manage, process, and analyze the data using the traditional database systems and software techniques. A great deal of the existing definitions tend to converge on three main attributes of big data: the huge *volume* of data, the wide *variety* of data types, and the *velocity* at which the data can be collected and analyzed.

The term 'big data analytics' denotes 'any vast amount of data that has the potential to be collected, stored, retrieved, integrated, selected, preprocessed, transformed, analyzed, and interpreted for discovering new or extracting useful knowledge. Prior to this, the analytical outcome (the obtained results) can be evaluated and visualised in an understandable format before their deployment for decision–making purposes (e.g., improving, adjusting, or changing an operation, function, service, strategy, or policy)… In the domain of smart sustainable urbanism, big data analytics refers to a collection of sophisticated and dedicated software applications and database management systems run by machines with very high processing power, which can turn a large amount of urban data into useful knowledge for enhanced decision––making and deep insights in relation to various urban domains, such as transport, mobility, traffic, environment, energy, land use, waste management, education, healthcare, public safety, planning and design, and governance' (Bibri, 2018b, p. 234).

4. A thorough analysis, evaluation, and discussion of the compact city paradigm of sustainable urbanism

4.1. The compact city model

4.1.1. Genesis and dimensions

The compact city model is considered one of the planning and development strategies that can achieve more sustainable cities in terms of their environmental, economic, and social goals. As an idea that is aligned with the goals of sustainable development, the compact city was envisioned by Dantzing and Saaty (1973) as a city that enhances the quality of life but not at the expense of the next generation. The concept of the compact city became more established in the early 1990s, after the widespread diffusion of sustainable development, as a result of the near clinical separation of land uses because of suburban sprawl that had risen the need for travel trips, creating an upsurge in automobile use which in turn caused high levels of air and noise pollution, in addition to decaying city centers. In this respect, the European Commission highlighted a number of negative trends in urban development in their Green Paper on the Urban Environment (CEC, 1990), and therefore argued for denser development, mixed land use, and the transformation of former brownfield sites rather than development in open green areas. According to Burton (2002), the 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 another view, the compact city is characterized by high–density and mixed land use with no sprawl (Jenks et al., 1996a, b; Williams et al., 2000) through urban intensification, i.e., infill, renewal, development, redevelopment, and so on. The compact city concept is associated with the term ‘urban intensification,’ which ‘relates to the range of processes which make an area more compact’ (Jenks et al., 1996a). It was around the mid–1990s when the research led to the advocacy of combining mixed land use and compactness (Jabareen, 2006). Mixed land use should be encouraged in cities (Breheny, 1992). In addition, the compact city emphasizes spatial diversity, social mix, sustainable transportation (e.g., transit–rich interconnected nodes), as well as high standards of environmental and urban management systems, energy–efficient buildings, closeness to local squares, more space for bikes and pedestrians, and green areas (Bibri, 2019a). It has been addressed and can be implemented at different levels, namely neighborhood, district, city, metropolitan, and region, and involves many strategies that can avoid all the problems of modernist planning and design in cities by enhancing the underlying environmental, economic, and social justifications and drivers.

There are multiple definitions of the compact city, as an urban planning and design concept, in the literature (e.g., Jabareen, 2006; Burton, 2001; Jenks et al., 1996a, b; Dempsey et al., 2010; Dempsey and Jenks, 2010; Neuman, 2005; Van Bueren et al., 2011). Most of these definitions 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. In other words, there is a diversity underneath the various uses of the term ‘compact city,’ adding to the convergence or divergence in the way projects and initiatives conceive of what a compact city should be. In fact, there are great differences between compact cities in terms of their form whose key elements can be distinguished: density, surface, land use, public transport infrastructure, and the economic relationship with the surrounding environment (Van Bueren et al., 2011). In addition, there is a difficulty in analyzing what a compact urban form is, and which of its elements contributes more to the goals of sustainable development. One explanation of the contradictory findings in research is consequently the persistent lack of a clear definition for what a compact city actually is (Neuman, 2005). The list of classifications provided in the UN–Habitat’s and other policy documents (e.g., UN Habitat, 2011, a, c; OECD, 2012a) is from a general perspective. Nevertheless, many cities having the highest level of sustainable development practices (e.g., Sweden, Norway, Finland, Germany, the Netherlands, etc.) have been studied on their compact development with the aim to contextualize the outcome to become practically applicable in other cities. Accordingly, lessons can (and should) be learned from other cities around the world. It is well understood that there cannot be a set of rigid, strict strategic guidelines to be implemented anywhere around the world to achieve sustainable urban forms. Sustainability depends on several intertwined factors which should fit the local context. In view of that, the local opportunities and constraints of each city need to be addressed in a more integrated approach given the complexity of urban systems in terms of social, economic, and environmental life (Newman and Jennings, 2008). In some instances, cities are evidently incomparable both in scale and in socio–cultural, political, and historical contexts, but the comparison can still be undertaken regarding the relative proportions of density and diversity across urban areas. Still, even if several attempts have been undertaken to establish ‘compact city’ indexes, the heterogeneity of the concepts of density (Churchman, 1999; Manaugh and Kreider, 2013) and diversity (Manaugh and Kreider, 2013), coupled with the prevalence of different indexes (Lee et al., 2015), is problematic for the practical implementation of policy. Therefore, the classifications listed in the UN–Habitat’s and other policy documents do not provide concrete guidelines for global implementation (Lim and Kain, 2016). All in all, each city should deal with its own urban development and form, applying the compaction strategy and implementing policies to improve the health of the city and the quality of life for the citizens.

Due to the above inconsistencies in urban research and its effect on practice as to planning policy, the concept ‘compact city’ risks becoming a ‘boundary object’ similar to the concept ‘sustainable development’ (Muraca and VogetöKleschin, 2011). As a means of translation used to connect different, or create intersections of separate, social worlds, a boundary object is interpreted and used differently by various actors or across communities in light of their own experiences, needs, constraints, and/or biases. In this case, the concept of the compact city becomes vague enough to justify any type of urban development (Leffers, 2015).

4.1.2. Core compact city principles and strategies

In this context, the term ‘principle’ means a proposition that serves as the foundation for the compact city model, and the term ‘strategy’ denotes an approach that is used to achieve the goals of sustainable development. The compact city model entails a set of common design principles and strategies. However, while many studies have been carried out on compact cities across the globe focusing on different approaches to compact urban planning and development, they do share the key dimensions of the compact urban form with a slight difference in details, as illustrated in Table 2.

Taking a closer look at Table 2, it becomes noticeable that the most common design principles and strategies underlying the compact city are compactness, density, land use and social mixes, sustainable transportation, and green space. These are briefly separately described next.

4.1.2.1. Compactness. Generally, compactness proposes the density of the built environment and the intensification of its activities, land–use mixture, diversity, sustainable transportation, and efficient land planning to protect natural and agricultural areas. A denser, more diverse city with a greater mix of uses together with sustainable transportation and green space is what many cities pursuing the path of sustainability, especially within the ecologically advanced nations, are striving to achieve and maintain through diverse policies, practices, and strategies by developing and implementing a number of measures to improve their contribution to the goals of sustainable development (e.g., Bibri et al., 2020; Hofstad, 2012). As a widely acknowledged strategy for achieving desirable urban forms, compactness is about contiguity and connectivity, which suggests that future urban development pertaining to the physical dimension of urbanization (land use change) should take place adjacent to existing urban fabrics or structures. Thus, the potential of currently existing building zones should be exploited to enable structural development in existing urban areas in the future based on strategies for inward development. This relates to the intensification of the built form, a major strategy which emphasizes more efficient land use by increasing the densification of development and activity (Jabareen, 2006). The intensification approach includes development of less or undeveloped urban land and transformation or redevelopment of previously developed sites, as well as extensions and additions and conversions and subdivisions (Jenks, 2000)

4.1.3. Density

Density is a critical strategy in determining the compact urban form. Urban density refers to the ratio of dwelling units or people to land area. However, achieving a compact city is not only about increasing density *per se* or across different spatial scales, but also about good planning to achieve an overall more compact urban form. This relates

Table 2
Approaches to and dimensions of compact urban form.

Scholars. Theorists, and Organizations	Focus of Studies	Dimensions
(UN Habitat, 2015)	Strategy of sustainable neighborhood planning	1 Adequate space for streets 2 Efficient street network 3 High density 4 Mixed land uses 5 Social mix 6 Limited land use specialization
(Jabareen, 2006)	Design concepts of sustainable urban forms and their contribution to sustainability	1 Compactness 2 Density 3 Mixed land uses 4 Diversity 5 Sustainable transport
(Kotharkar et al., 2014)	Measuring compact urban form	1 Density 2 Density Distribution 3 Mixed land uses 4 Transportation network 5 Accessibility 6 Shape
(Jones and Macdonald, 2004)	Sustainable urban form components and economic sustainability	1 Mixture of Land uses 2 Density 3 Transport infrastructure 4 Characteristics of built environment 5 Layout
(Dempsey et al., 2010)	Sustainable urban form components	1 Density 2 Mixed land uses 3 Transport infrastructure 4 Accessibility 5 Built environment characteristics 6 Urban layout
(Song and Knaap, 2004)	Quantitative measure of urban form	1 Density 2 Mixed land uses 3 Pedestrian access 4 Accessibility 5 Street design and circulation system
(OECD, 2012b)	Policies of compact city: a comparative assessment	1 Compactness 2 Impact of compact city policies
(Bertaud, 2001)	Analysis of spatial organization of large cities	1 Spatial Distribution of Population 2 Spatial Distribution of Trips 3 Average density and land consumption 4 Density profile 5 Population by distance to center of gravity
(Bibri et al., 2020)	Urban planning practices and development strategies for sustainable development	1 Density 2 Compactness 3 Mixed land use 4 Diversity 5 Sustainable transportation 6 Green space
(Neuman, 2005)	Static versus dynamic planning and design. i.e., forms versus processes	1. High residential and employment density 2. Mixture of land uses 3. Fine grain of land uses (proximity of varied uses and small relative size of land parcels) 4. Increased social and economic interactions 5. Contiguous development (some parcels/structures may be vacant or abandoned or surface parking) 6. Contained urban development, demarcated by legible limits 7. Urban infrastructure, especially sewerage and water mains 8. Multimodal transportation 9. High degrees of accessibility: local/regional 10. High degrees of street connectivity (internal/external), including sidewalks and bicycle lanes 11. High degree of impervious surface coverage 12. Low open—space rat 13. Unitary control of planning of land development, or closely coordinated control 14. Sufficient government fiscal capacity to finance urban facilities and infrastructure

to strategic future urban development associated with the potential for higher densities through densification.

4.1.3.1. Land–Use mix and social mix. Land use refers to the distribution of functions and activities across space, grouped into different categories. Widely recognized for its important role in achieving sustainable urban form, land–use mix denotes the diversity and proximity of compatible land uses, a form of cross–sectional residential, commercial, institutional, and cultural infrastructures associated with living, working, and service and amenity provision. As a preferred typology in sustainable urban planning and development, diversity, which overlaps with land–use mix as to the variety of land uses, entails building densities, housing for all income groups through inclusionary zoning, a variety of housing types, job–housing balances, household sizes and structures, cultural diversity, and age groups, thereby representing the socio–cultural context of the compact city (Bibri, 2019a). Indeed, diversity has been used interchangeably with social mix (housing types and options, demographics, lifestyles, etc.) in the literature. Suggested to be achieved by the availability of different housing options in terms of price ranges, tenure type and building types, and the availability of diversity of jobs in the proximity, social mix is defined as the presence of residents from different backgrounds and income levels in the same neighborhood (UN Habitat, 2015).

4.1.3.2. Sustainable transportation. Sustainable transportation means services that reflect the full social and environmental costs of their provision; that balance the needs for mobility and safety with the needs for accessibility, environmental quality, and neighborhood livability; and that have enough carrying capacity (Jordan and Horan, 1997). It is a key strategy for achieving sustainable urban forms. Indeed, it is by relying on sustainable transportation that the dense, diverse, and mixed–use patterns characterizing the compact city enable it to secure environmentally sound, economically viable, and socially beneficial development (Bibri, 2020). As a key component of sustainable transportation, in addition to cycling and walking, the public transport system represents one of the most important driving factors in order to reach a more sustainable city. The public transport system involves both the physical infrastructure, including roads, railroad tracks, and sidewalks, as well as the level and quality of services provided to citizens, e.g., great buss and train frequency and faster journey time. As regards the advantages of sustainable transportation, it operates the transport system at maximum efficiency, provides favorable conditions for energy–efficient forms of transport, limits CO_2 emissions, allows equitable accessibility to services and facilities, promotes renewable energy sources, decreases travel needs and costs, minimizes land use, and supports a vibrant economy

4.1.3.3. Green space. Greening of the city is an important design concept for sustainable urban forms. Green space has the ability to contribute positively to some key agendas of sustainability in urban areas (Swanwick et al., 2003). Green space can be defined as the areas of nature found in the urban landscape. It includes trees, grassy patches, water features, flowerbeds, and rock gardens. For example, Swedish cities operate with the concept of 'green structure' in their compact planning and development, which comprises larger green areas, waterways and streams, shorelines, city parks, agricultural land, and natural areas as one common structure (Bibri, 2020; Bibri et al., 2020). Green structure plans emphasize the benefits and losses of green structures.

4.2. The compact city ideal: benefits and effects

As widely acknowledged, the image of the compact city has proven to be a highly influential translation of what a sustainable city should be, carried by the significance of the design principles and strategies underlying this model of sustainable urban form. Ideally, a compact city secures environmentally sound, socially beneficial, and economically viable development through dense and mixed–use patterns that rely on sustainable transportation (Bibri, 2020; Burton, 2000, 2002; Dempsey, 2010; Dempsey and Jenks, 2010; Jenks and Dempsey, 2005; Jenks and Jones, 2010). A well–designed compact city should be able to achieve all of the benefits of sustainability; in view of that, the compact city becomes an all–encompassing concept for urban planning practices (Dempsey and Jenks, 2010). The compact city is more energy efficient and less polluting because people live in close proximity to workplaces, shops, and leisure and service facilities, which enables them to walk, bike, or take transit. This is in turn anticipated to create a better quality of life by creating more social interaction, community spirit, and cultural vitality (Jenks and Jones, 2010). Further, travel distances between activities are shortened due to the heterogeneous zoning that enables compatible land uses to locate in close proximity to one another—-mixed land uses. Such zoning primarily reduces the use of automobiles (car dependency) for commuting, leisure, and shopping trips (Alberti, 2000; Van and Senior, 2000). Integrating land use, transport, and environmental planning is key to minimizing the need for travel and to promoting efficient modes of transport (Sev 2009). Transport systems play particularly an important role in the livability of contemporary cities (Newman and Kenworthy, 1999). The interrelationship between transport, people, and amenities are argued to be the vital elements of the micro–structure of a sustainable city (Frey, 1999). Important to note is that population densities are sufficient for supporting local services and businesses (Williams et al., 2000) in terms of economic viability. In high density development, more land is available for green and agricultural areas, public transport services are superior, and the environmental footprint of the non–renewable resource consumption is steady (Suzuki et al., 2010).

In sum, the compact city model has been advocated as the most sustainable urban form due to several reasons: 'First, compact cities are argued to be efficient for more sustainable modes of transport. Second, compact cities are seen as a sustainable use of land. By reducing sprawl, land in the countryside is preserved and land in towns can be recycled for development. Third, in social terms, compactness and mixed uses are associated with diversity, social cohesion, and cultural development. Some also argue that it is an equitable form because it offers good accessibility. Fourth, compact cities are argued to be economically viable because infrastructure, such as roads and street lighting, can be provided cost–effectively per capita.' (Jabareen, 2006, p. 46)

4.3. Compact city issues, policies, and research approaches

There is a large body of empirical work on compact cities, especially in the form of case studies. Such work tends to focus on a range of the environmental, economic, social, and physical issues of sustainability, as well as the policy and planning practices and development and design strategies for achieving the goals of sustainable development. A set of recent studies is selected and compiled in Table 3. As to the theoretical work, studies on compact cities have approached the topic from one or a combination of these perspectives: planning theory, design theory, architectural theory, resilience theory, scale theory, spatial analysis, human geography, complexity theory, systems theory, action net theory, actor network theory, regenerative design, and causal relationship, in addition to a number of varied discursive studies, critical studies, comparative studies, and so on.

4.4. Compact city design strategies and their link to the goals of sustainable development: an empirical basis

Societies are ever changing and urban planning and development need to adapt to and keep up with global shifts and transitions. Hence, policies and strategies associated with compact cities need to be constantly assessed, adjusted, and improved in response to major trends while suiting the local context. This involves the quest for achieving and balancing the goals of sustainable development. This debate has been going on for decades now and will continue to go on well into this new millennium. However, sustainable urban visions, policies, and strategies are developed along the lines of argument supported by, among others, European Union policy documents that a compact city structure has positive effects on efficient use of resources, economic development, and citizen well–being (CEC, 2011); that compact city policies result in reduced energy consumption and emissions in transportation at different spatial scales, in conservation of farmlands and biodiversity, and in reduction of infrastructure cost and increase of

Table 3
Examples of case studies.

Country	Issues	Policies
Gothenburg and Helsingborg, Sweden (Bibri et al., 2020)	Urban development Socio–economic segregation Open green space preservation Increased congestion High immigration	Master Plan for Helsingborg City Comprehensive Plan for Gothenburg City The Concept of Compact City Green Infrastructure
Paris, France (OECD, 2012b)	Urban development Car dependency Loss of green space	Regional development agenda Grand Paris Express connection
Lau et al. 2002	Urban development Traffic congestion Urban sprawl growth High immigration Flat land shortage	The Concept of Vertical City The Concept of Compact City The Concept of Sky City
Melbourne, Australia (OECD, 2012b)	Decline in economic sectors Rapid urban growth Increased car and truck ownership Urban sprawl growth	Revitalization of Central Melbourne Deregulation policies on and conversion of land use
Amsterdam, Netherland (Nabielek, 2012)	Scattered development Increased congestion High urbanization Urban sprawl growth High immigration	The Structure Plan The National Environmental Policy Plan The National Policy on Spatial Planning
Tokyo and Gothenburg (Lim and Kain, 2016)	Density of built objects Scales of built objects Distribution of the diversity of built objects	The Concept of Compact City Comprehensive Plan for Gothenburg Master Plan for Tokyo Planning by Design Planning by Developmental Control Planning by Coding/Rule-based Planning
Auckland, New Zealand (Arbury, 2005)	Rapid urban growth Car dependency Transportation system Urban sprawl growth	Regional Growth Strategy for Compact Development Regional Growth Strategy 2050
Toyama, Japan (OECD, 2012b; Suzuki et al., 2010)	Increasing car dependency Population density decline Urban centers decline Agricultural land decline	Master Plan for Toyama City Toyama Compact City Model The City's Density Target and Grant Program

labour productivity (OECD, 2012a); and that cultural, social, and political dynamics are promoted by density, proximity, and diverse choices available within compact cities (CEC, 1990).

Many recent empirical studies have addressed the extent to which the compact city model produces the claimed environmental, economic, and social benefits of sustainability, especially in relation to those nations known for their high profile of sustainable development practices. These include, according to several rankings, Sweden, Norway, Finland, Germany, the Netherlands, and Japan (Dryzek, 2005). Important to highlight, before delving into the discussion of the key issues, compact cities, whether within these nations or elsewhere, tend to exhibit differences, at varying degrees, in the way they practice the compact city model in terms of the application of the underlying design principles and strategies (see, e.g., Bibri et al., 2020; Hofstad, 2012; Lim and Kain, 2016). This is due to their specific physical, geographical, socio–-political, cultural, and historical aspects, especially in regard to urban planning and development practices and strategies. Besides, there are great differences between cities in terms of their urban form as to its key constituting elements (e.g., Van Bueren et al., 2011), and the local opportunities and constraints of each city need to be addressed in a more integrated approach (Newman and Jennings, 2008).

The compact city as a set of planning and development practices and strategies is justified by its ability to contribute to the environmental, economic, and social goals of sustainable development. This corresponds to the results obtained from empirical studies (e.g., Bibri et al., 2020; Hofstad, 2012). In fact, the centrality of the compact city ideal and especially its three sustainability dimensions in urban planning and development is found throughout the western world (Easthope and Randolph, 2009; Healey, 2002; Portney, 2002; Raman, 2009; Vallance et al., 2005). The measures of the compact city give a series of environmental, economic, and social benefits as they are designed to revitalise existing city areas, increase walking and cycling, enhance the use of public transportation, and preserve recreational and open green space (Jenks and Jones, 2010). The compact city model provides better economic outcome (Quigley, 1998), reduces energy consumption and pollution through densification (Breheny, 1995; Mindali et al., 2004), and alleviates social segregation (Burton, 2001).

Concerning environmental sustainability, compact cities aim to decrease travel needs and thus mitigate emissions through walking, cycling, and public transport; to reduce the pressure on green and natural areas; and to conserve energy through building densities that support combined heat and power systems. The main environmental aspects, namely sustainable travel and land efficiency, constitute a central part of planning and development practices in both Copenhagen and Oslo (Næss et al., 2011a,b). The work of Newman and Kenworthy (1999) provides the evidence that the compact urban form is associated with a high use of public transports and less energy consumption. In relation to this, most of the collective transports are powered by electricity, and when this is generated by renewable energy (i.e., solar, biofuel, wind, etc.), the reduction of emissions is very significant. Transport is arguably the single biggest issue for environmental debates relating to urban form (Jenks et al., 1996a).

Furthermore, several compact cities promote green space and natural areas. They share the research view that it is possible to attain a city that is both compact and green, according to an empirical study conducted by Bibri et al. (2020). As concluded by Hofstad (2012), urban green areas targeted by development strategies enhance the presence of compact city ideas through the discourse and institutionalization of green structure plans. Especially, natural areas are regarded as valuable recreational facilities and a way of making the city more healthy and vibrant, in addition to contributing to protecting biodiversity and ecosystem services (Bibri, 2020; Bibri et al., 2020). The research in this area tends to focus on the health advantages of urban green space (De Vries et al., 2002; Maas et al., 2006). It is crucially important for new approaches to urbanism to incorporate more ecologically responsible forms of settlement and living (Beatley, 2000).

Green space has the ability to contribute positively to the agendas of sustainability in urban areas (Swanwick et al., 2003). However, green space is a subject of debate due primarily to the core conception of the compact city model. In this respect, the argument that the compact urban form will reduce the pressure on green areas, ecosystem services, and biodiversity is less certain. While the goal of protecting large green areas outside strategic nodes through densification usually finds support, it is more uncertain when it comes to green areas located in or close to the urban fabric given the potential enticing opportunities for the new urban development projects to strengthen the economic goals of sustainability through compact city strategies (Bibri et al., 2020).

Of relevance to point out is that greening urban areas as an important design approach is typically associated with the concept of the eco–city as another prevailing sustainable urban form, so too is passive solar design. As an important concept for achieving sustainable urban forms, passive solar design entails reducing the demand for energy by using solar passive energy sustainably through particular design measures applied to buildings and urban densities. It positively affects the urban form as to its environmental health (e.g., Jabareen, 2006). However, this design principle and strategy is not part of the compact city model, despite the intensification of development as a major strategy for compactness. The orientation of buildings and urban densities as a design feature affects the form of the built environment (Thomas, 2003). Bibri (2019a) provides an account of passive solar design and its benefits in relation to sustainable urban forms. However, another design principle and strategy of the eco–city that is also of high pertinence to the compact city as regards to its environmental health is 'smart urban metabolism' (Shahrokni et al., 2015). As argued by Marcotullio (2017), sustainable systems are a key innovation that the compact city needs to adopt because they create the infrastructure to naturally process sewage waste, grey water, and storm runoff on–site, in addition to preventing flooding on the urban hardscape and utilizing wastewater to fertilize and water gardens. The eco–city manages an ecologically beneficial waste management system that promotes recycling and reuse to create a zero-waste system (Roseland, 1997).

Nevertheless, the compact city and eco–city models have many overlaps between them in their concepts, ideas, and visions, with some distinctive concepts and key differences for each one of them. According to Roseland (1997) and Harvey (2011), an ideal eco–city has a well–designed urban layout that promotes walkability, biking, and the use of public transportation system; ensures decent and affordable housing for all socio–economic and ethic groups; and supports future expansion and progress over time. Indeed, Bibri and Krogstie (2019b) argue for a complete amalgamation of the compact city model with the eco–city model based on the following rationale as grounded in a detailed literature review:

- Being one of the most significant intellectual and practical challenges for three decades, the development of a desirable model of sustainable urban form continues to motivate and inspire collaboration between researchers, academics, and practitioners to create more effective design and planning solutions based on a more integrated and holistic perspective.
- A critical review of planning approaches (e.g., compact cities and eco-cities) demonstrates a lack of agreement about which form is the most sustainable and environmentally sound.
- Different scholars and planners may develop different combinations of design concepts to achieve the goals of sustainable development. They might come with different forms, where each form emphasizes different concepts and contributes differently to sustainability.
- Sustainable urban forms have many overlaps among them in their concepts, ideas, and visions. While there is nothing wrong with such forms being different yet compatible and not mutually exclusive, it can extremely be beneficial and strategic to find innovative ways of combining their distinctive concepts and key differences towards more holistic forms for improving sustainability performance.
- Compact cities have a form as they are governed by static planning and design tools, whereas eco–cities are amorphous: without a clearly defined form, thereby the feasibility and potential of their integration into one model that can eventually accelerate sustainable development towards achieving the optimal level of sustainability.
- Neither real–world cities nor academics have yet developed convincing models of sustainable urban form, and the components of such form are still not yet fully specified.
- More in–depth knowledge on planning practices is needed to capture the vision of sustainable urban development, so too is a deeper understanding of the multi–faceted processes of change to achieve sustainable urban forms. This entails conceptualizing multiple pathways towards attaining this vision and developing a deeper understanding of the interplay between social and technical solutions for sustainable urban forms.

With respect to economic sustainability, compact cities aim to revitalize the city centers through the promotion of densely built dwellings, shops, businesses, services, and accessible transportation; to create proximity between people and their workplaces, thus making sustainable travel possible; to promote greater diversity among employers and job possibilities; to enhance commercial properties and housing markets, and to improve public transportation infrastructure (see, e.g., Bibri et al., 2020; Hofstad, 2012; Jenks and Jones, 2010; OECD, 2012b) Additionally, economic development is found to be a significant force in bringing about densification in studies undertaken in Sweden, Norway, and Denmark (Bibri et al., 2020; Hofstad, 2012; Mace et al., 2010; Næss et al., 2011a,b). Of relevance to highlight moreover is that proximity, how close jobs, amenities, and services are to where people live as generally calculated based on the travel time and distance to their homes, adds another dimension to the compact city: self–sustaining. This means that the city has everything that people need within the community, including stores, employers, service providers, energy generation, waste disposal and processing, and small–scale agricultural production (community gardens and/or vertical gardening) (Li and Yu, 2016). Again, the latter is typically associated with the concept of the eco–city (Harvey, 2011; Roseland, 1997).

As to social sustainability, compact cities tend to tie its goals to densification together with social, physical land use, temporal, and economic mixes. They aim to improve social integration, social cohesion, social capital, and public safety, as well as the quality of life through social interaction and ready access to services and facilities and to open green space and recreational areas (e.g., Bibri et al., 2020). With respect to the latter, compact cities aims highlight the creation of an amalgam of dwellings, businesses, shops, amenities, and facilities that makes daily life simpler and life–long living possible, and creates diverse population and vital city centers and green and recreational areas for a healthy and vibrant city (Bibri et al., 2020; Hofstad, 2012). Mixed use development promotes vitality and diversity, thereby providing very significant benefits (Arbury, 2005). As regards the former, the main problems compact cities struggle with include socio–economic segregation and social inequity (Bibri et al., 2020); Hofstad, 2012). The compaction strategy supports and promotes the fairness of the distribution of resources, reducing the gap between the advantaged and the disadvantaged (Burton, 2001). One of the arguments which supports social equity is the possibility to have a better access to services and facilities (Burton, 2000). There also is evidence that compactness encourages social equity through the reduction of social segregation (Burton, 2001).

In view of the above, the economic goals seem to dominate over the environmental and social goals, notwithstanding the general claim about the three dimensions of sustainability being equally important at the discursive level. It can be argued that there is a goal hierarchy between the three dimensions of sustainability in compact city planning and development. This is consistent with the conclusion drawn by

Hofstad (2012) that the economic goals remain at the core of planning, while the environmental and social goals play second fiddle, and also by Bibri (2020) that the former dominate over the latter in planning practices and development strategies. Nonetheless, compact cities have the ability to respond to different socio–economic and environmental issues while emphasizing the quality of life.

4.5. The compact city paradox:Conflicting and contentious issues

Although research and policy argue for more compact cities, referring to higher density, diversity, mixed land use, sustainable transportation, and green areas, they are, as with all sustainable development approaches, associated with some conflicts. To begin with, the compact city model produces high levels of noise pollution due to the close proximity between dwellings, transport lines, business activities, and service facilities (De Roo, 2000). Thus, the concentrated impact of dense populations on the environment and the lack of planning for noise pollution control prevent the desired outcomes of this model from being achieved, e.g., direct negative health effects. Moreover, a number of studies (e.g., Breheny, 1992, 1997; Neuman, 2005) argue that compact urban developments can increase land and dwelling prices, cause severe congestion in transport, and create social exclusion. Also, it is argued that neighborhood density might impact negatively on neighborhood satisfaction (Bramley and Power, 2009), sense of attachment, and sense of the quality of public utilities (Dempsey, Brown and Bramley 2012). Breheny (1997) examines empirical data regarding the effects of the compact policies on the population, and concludes that it is deeply unsatisfied about the higher-density of dwellings development. Research asserts that more dense urban areas are often responsible for high crime levels (Burton, 2000).

In addition, arguing against the concept, critics of the compact city highlight increased ecological footprint due to higher consumption, larger income gaps (Heinonen and Junnila, 2011), decreased living space for low income groups, and accessibility issues to green and natural areas (Burton, 2001). The first two issues might be linked to low income population in dense urban areas, rather than to the urban form itself (Glaeser, 2011). They may also be attributed to a design problem and not necessarily linked to urban compactness given that crowding is a problem of perception of urban space (Kearney, 2006). Similarly, negative social problems related to density may be due to the characteristics of the urban areas in terms of poverty concentration, rather than to the urban form itself (Bramley and Power, 2009). Accordingly, urban problems and urban form are not clearly correlated. There is a risk that generic problems of urbanization are criticized as being problems of the compact city (Lim and Kain, 2016). As Glaeser (2011, p. 9) puts it: 'Cities do not make people poor; they attract poor people. The flow of less advantaged people into cities from Rio to Rotterdam demonstrates urban strength, not weakness.'

The debate over the compact city as a set of planning and development strategies is actually between two groups: the 'decentrists', in favour of a decentralised form, and the 'centrists', in favour of a high-density compact form. Breheny (1996) discusses the view on the future of urban form in relation to decentrists, centrists, as well as compromisers. Based on the literature, the main critical arguments of the compact city are advanced by the decentrists who are skeptical on the environmental benefits delivered by the strategy; claim that the expected energy reduction is modest compared to the discomfort caused by the necessary rigorous policies; and believe that it is impossible to halt the urban decentralisation phenomenon that fits the attitudes of the major part of the population. And this majority prefers to live in the tranquillity of rural and semi-rural areas, far away from the chaotic city. In short, the dominant reasons for the heated debate revolve around GHG emissions, energy consumption, and the loss of open green areas in favor of the rapid urbanization. A key point against the compact city model regards the loss of urban green spaces in the cities and the inevitable development of green fields outwards due to the increased congestion and high-density development (Breheny, 1996).

As another line of argument, policy makers have been 'cherry-–picking those aspects of the compact city as a sustainable urban model most attractive to their needs, such as increasing densities and containing urban sprawl…, which largely reflect dominant economic or environmental interests' (Dempsey and Jenks, 2010, p. 119). While this may well hold, it is also safe to argue that developing robust alternatives in the face of the hegemony of unsustainable economic development within urban planning takes time (Hofstad, 2012), not to mention for such transformation to reshape existing socio-technical configurations.

Worth pointing out is that the above conflicting and contentious issues are still largely associated with the whereabouts of the compact city as to its implementation and development, and what types of planning approaches are adopted to promote dense and diverse urban patterns. With regard to the former, according to Breheny (1997), the conclusions of many studies are pretty vague and vary from case to case when it comes to the environmental benefits delivered from the compaction strategy. With respect to the latter, there is a need to focus planning evaluation on the implementation of plans, particularly in the context where urban form attracts growing interest as the spatial concretization of urban sustainability (Oliveira and Pinho, 2010). This pertains particularly to those countries with high level of sustainable development practices. In relation to this argument, as urban planning generally takes place in open systems with many purposeful parts (i.e., people and organizations pursuing their interests), it is difficult to link planning activities to outcomes in the urban reality (Laurian et al., 2010). Nonetheless, there are highly institutionalized planning systems (e.g., Sweden) to increase the likelihood that planning indeed affects the urban reality. Lim and Kain (2016) examines the differences in the outcome of the different planning approaches in Sweden and Japan in relation to urban characteristics, such as density and diversity.

4.6. Compact city planning and development problems, issues, and challenges

4.6.1. Deficiencies, limitations, fallacies, and uncertainties

As a model of sustainable urban form, the compact city involves a number of problems, issues, and challenges when it comes to planning, design, and development at the technical and policy levels in the context of sustainability. Bibri and Krogstie (2019a) provide a detailed review of sustainable urban forms in terms of deficiencies, limitations, fallacies, and uncertainties, as well as new opportunities and prospects offered by advanced ICT, especially big data technologies and their novel applications. A tabulated version of the outcome of this review is provided in Bibri and Krogstie (2019a). To elaborate on one of the key issues related to this paper: the fallacy of the compact city, Neuman (2005) contends that conceiving cities in terms of forms remains inadequate to achieve the goals of sustainable development; or rather, accounting only for urban form strategies to make cities more sustainable is counterproductive. Instead, conceiving cities in terms of 'processual outcomes of urbanization' holds great potential for attaining these goals, as this involves asking the right question of 'whether the processes of building cities and the processes of living, consuming, and producing in cities are sustainable,' which raises the level of, and may even change, the game (Neuman, 2005). Monitoring, understanding, and analyzing this set of processes can well be enabled by advanced ICT to further improve sustainability in the face of urbanization. Another argument advanced by Neuman (2005, p. 22) is also of relevance in this regard: 'form is both the structure that shapes process and the structure that emerges from a process'. If form 'is an outcome of evolution' (Neuman, 2005, p. 23), then the arrangement of how planning is undertaken to support and guide such an evolutionary process becomes an issue of importance (Lim and Kain, 2016). In relation to this argument, a well–established fact is that cities evolve and change dynamically as urban environments, so too is the underlying planning and design knowledge that perennially changes in response to new emergent factors. To put it differently, cities need to be dynamic in their conception, flexible in their planning, scalable in their design, and efficient in their operational functioning in order to be able to deal with population growth, environmental pressures, and changes in socio–economic needs, in addition to keeping up with global shifts/trends, discontinuities, and societal transitions (Bibri, 2019a). Durack (2001) argues for open, indeterminate urbanism due to its advantages, namely the tolerance and value of topographic, social, and economic discontinuities; continuous adaptation; and citizen participation, which is common to human settlements. This alternative approach to urbanism 'recognizes discontinuities and inconsistencies as life-affirming opportunities for adaptation and change, offering choices for the future in accordance with the true definition of sustainability' (Durack, 2001, p. 2). In light of the above, it is timely and necessary to develop and apply more innovative solutions and sophisticated approaches to deal with the challenges of sustainability and urbanization by incorporating them in urban planning, design, management, and operational functioning processes due to the dynamic, synergistic, substantive, and disruptive effects of advanced technologies. This relates to urban intelligence functions, which represent new conceptions of how sustainable cities function and utilize and combine complexity science and urban science in constructing powerful forms of urban simulations models and optimization and prediction methods that can generate urban forms, structures, and systems that improve sustainability, efficiency, resilience, equity, and the quality of life (Bibri, 2019a, b). As pointed out by Durack (2001), accepting indeterminacy demands much more than settling for the structures of an immutable order, and adopting sustainability as a sincere objective requires planning and developing cities 'not only in closer correspondence with nature, but also in recognition of the process of life itself'.

4.6.2. Wicked problems in sustainable urbanism and the relevance of big data science and analytics

Generally, cities epitomize complex systems, more than the sum of their parts, and are developed through an array of multitudinous individual and collective decisions. As such, they are full of contestations and conflicts that are not easily captured and steered. The problems of cities are primarily about people and their environment and life. Physical, infrastructural, environmental, economic, and social issues in cities represent 'wicked problems', a term that has gained currency in urban planning and policy analysis, especially after the adoption of sustainability within urban planning since the early 1990s (Bibri, 2019a). In short, cities are characterized by wicked problems (Rittel, 1969; Rittel and Webber, 1973), i.e., difficult to define, unpredictable, and defying standard principles of science and rational decision-making. In order to describe a wicked problem in sufficient detail, one has, as stated by Rittel and Webber (1973), 'to develop an exhaustive inventory of all conceivable solutions ahead of time. The reason is that every question asking for additional information depends upon the understanding of the problem—and its resolution—at that time… Therefore, in order to anticipate all questions (…all information required for resolution ahead of time), knowledge of all conceivable solutions is required.' One implication of this is that when tackling wicked problems, they become worse due to the unanticipated effects and unforeseen consequences that were overlooked, because the systems in question were not approached from a holistic perspective, or were treated in too immediate and simplistic terms. The essential character of wicked problems is that they, according to Rittel and Webber (1973), cannot be solved in practice by a central planner. Bettencourt (2014) reformulates some of their arguments in a modern form in what is called the 'planner's problem,' which has two distinct facets: (1) the knowledge problem and (2) the calculation problem. The first problem refers to the planning data needed to map and understand the current state of the smart sustainable city in this context. It is conceivable that urban life and physical infrastructure could be adequately sensed in several million places at fine temporal rates, generating huge but manageable rates of information flow by the advanced forms of ICT. It is not impossible, albeit still implausible, to conceive and develop technologies that would enable a planner to have access to detailed information about every aspect of the infrastructure, services, social lives, and environmental states in a smart sustainable city. The second problem refers to the computational complexity to carry out the actual task of planning in terms of the number of steps necessary to identify and assess all possible scenarios and choose the best possible course of action. Unsurprisingly, the exhaustive approach of assessing all possible scenarios is impractical due to the fact that it entails the consideration of impossibly large spaces of possibilities. However, Bibri (2019d) sheds light on the wicked problems associated with smart sustainable urbanism and explores the usefulness of big data uses within this domain, as well as discusses the relevance of urban science and data–intensive science, as informed and enabled by big data science and analytics respectively, to what has been termed as urban sustainability science. The author argues that the upcoming advancements in big data science and analytics and the underpinning technologies, coupled with the ever–increasing deluge of urban data, hold great potential to advance smart sustainable urbanism as well as urban sustainability science. His work highlights the transformative power of big data science and analytics as a new area of science and technology with respect to revolutionizing urban sustainability science through data–intensive science, as well as contributes to bringing data–analytic thinking to the practice of smart sustainable urbanism.

Additionally, solutions to wicked problems require a great number of people to change their mindsets, and demand the input of multiple academic disciplines with relevant practical expertise, and the key is enabling these disparate experts to work together. Interdisciplinary research is an essential aspect of recent urban policies that create an environment for technological innovation in thinking about wicked problems. This requires that researchers work side–by–side with industry, local communities, policymakers, and decision–makers. Especially, to tackle wicked problems requires new technology research and development combined with implementation in practice. Indeed, interdisciplinary research alone is not sufficient to deal with wicked problems. To add, the poor understanding of how different development drivers, which are active within multiple sectors and involve multiple governance levels, co–produce compact cities is a key issue and concern that should be addressed to facilitate societal sustainability.

In light of the above, it is of crucial importance to develop and employ innovative solutions for solving, and sophisticated approaches into dealing with, the problems and challenges of sustainability and urbanization as of a wicked nature. This requires, among other things, a blend of sciences for creating powerful urban design principles and urban engineering analytical solutions. And advanced ICT, especially big data computing and the underpinning technologies, is extremely well placed to initiate this endeavor given that its application to urban systems, domains, networks, and related processes and practices is founded on the integration of computer science, data science, urban science, complexity science, (Batty et al., 2012; Bibri, 2019a, 2020; Bibri and Krogstie, 2017b; Bettencourt, 2014; Kitchin, 2014a, 2015, 2016), sustainability science, and data–intensive science (Bibri, 2019e), especially in regard to what has come to be identified as urban sustainability science (Bibri, 2019d). As an emerging scientific discipline, urban sustainability science integrates urban sustainability and sustainability science and is informed by urban science and data–intensive science, which are in turn informed by big data science and analytics (see Bibri, 2019d for a conceptual framework). A recent study conducted by Bibri (2019e) examines the unprecedented paradigmatic and scholarly shifts that the sciences underlying smart sustainable urbanism are currently undergoing in light of big data science and analytics and the underpinning technologies, and further discusses how these shifts intertwine with and affect one another in the context of sustainability.

In this work, the main sciences on focus are urban science, sustainability science, and urban sustainability science, and the paradigmatic and scholarly shifts are brought about by data–intensive science. The author argues that data–intensive science, as a new epistemological shift, is fundamentally changing the scientific and practical foundations of urban sustainability. In specific terms, he elaborates, the new urban science—a field in which big data science and analytics is practiced and which is informed by urban sustainability science—is increasingly making cities more sustainable, resilient, efficient, and livable by rendering them more measurable, knowable, and tractable in terms of their operational functioning, management, planning, development, and governance.

4.7. Towards data–driven smart sustainable urban forms

4.7.1. Advances in sustainable urban planning and development: data–driven smart solutions

The role of innovative ICT–enabled solutions in advancing urban sustainability is becoming evident in the light of the rapidly evolving theoretical and practical work concerned with the integration of sustainable cities and smart cities in a variety of ways. The need for advanced ICT in its various forms to be embedded into and pervade the built environment is underpinned by the recognition that urban sustainability applications are of high relevance and importance to the research agenda of computing and ICT (Bibri and Krogstie, 2016), especially big data science and analytics (Bibri, 2019a,d,e,f). To unlock and exploit the underlying potential, the field of sustainable urbanism needs to extend its boundaries and broaden its horizons beyond the ambit of the built form and ecological design of cities to include technological innovation opportunities and data analytics/computational capabilities.

Sustainable urbanism is a complex issue, with myriad problems surrounding urban systems. This is coupled with sustainable cities facing unprecedented physical, environmental, economic, and social challenges pertaining to urbanization. Therefore, sustainable cities are embracing the advanced forms of ICT, especially big data technology and its novel applications, to turn themselves into smart sustainable cities. Indeed, a new era is presently unfolding wherein smart sustainable urbanism is increasingly becoming data–driven (Bibri, 2019a). Yet, data–driven smart sustainable cities are increasingly becoming more complex with the very technologies being used to understand and deal with them as to their planning, design, operational functioning, development, and governance. Hence, there is a need for more innovative solutions and sophisticated approaches as to the way they can be monitored, understood, analyzed, planned, and designed so as to be effectively operated, managed, and, thus, develop in line with the long–term goals of sustainability. This can be accomplished by developing and applying advanced technologies as new conceptions of how data–driven smart sustainable cities function. In this respect, cities can only be smart and sustainable if there are intelligence functions that are able to integrate and synthesize urban data to improve environmental and social sustainability, efficiency, resilience, and the quality of life (Batty et al., 2012; Bibri, 2019c) through enhanced decisions about the physical, spatial, environmental, economic, and social forms of the city. Especially, building models of cities functioning in real time from routinely and automatically sensed data is becoming the new reality, coupled with urban ubiquitous sensing getting closer to providing quite useful information about longer term changes (Batty et al., 2012; Kitchin, 2014b).

With the above in regard, Bibri (2020) examines data–driven smart sustainable urbanism, focusing on new urban intelligence functions and related processes, systems, and sciences, and further proposes and illustrates a conceptual framework for data–driven smart sustainable cities on the basis of advanced technologies and new sciences. The author argues that urban intelligence functions as new conceptions of how data–driven smart sustainable cities function play a pivotal role in facilitating the synergy between their planning, design, operational functioning, development, and governance in terms of producing the benefits of sustainability. And that the upcoming developments and innovations in big data computing and the underpinning technologies, coupled with the unfolding and soaring deluge of urban data, hold great potential for enhancing and advancing smart sustainable urbanism practices. As to the proposed framework, it represents a conceptual structure intended to serve as a support or guide for building the model of data–driven smart sustainable cities that expands the structure into something useful on the basis of further qualitative analyses, empirical investigations, and practical implementations. The author's work is meant to contribute to bringing data–analytic thinking and intelligence to the domain of smart sustainable urbanism, and draws special attention to the clear prospect of big data science and analytics to transform the future form of such urbanism and to tackle the kind of complexities it embodies. All in all, new circumstances require new responses as regards smart sustainable urbanism and what it poses as complex challenges for traditional simulation, prediction, and optimization modelling.

In addition, Bibri and Krogstie (2017b) explores and substantiates the real potential of advanced ICT to evaluate and improve the contribution of sustainable urban forms to the goals of sustainable development. This entails merging big data technologies and their applications with the design principles and strategies of sustainable urban forms to achieve multiple hitherto unrealized goals. Further, the authors propose a matrix to assist scholars and planners in understanding and analyzing how and to what extent the contribution of such forms to sustainability can be improved through advanced ICT. They also put forward a data-driven approach into investigating and evaluating this contribution as an alternative to traditional data collection and analysis methods, as well as a simulation method for strategically optimizing this contribution. To extend this word, Bibri and Krogstie (2018) develop, illustrate, and discuss a systematic framework for data–driven urban analytics and 'big data' urban studies in relation to the domain of sustainable urbanism based on cross–industry standard process for data mining. This endeavor is in response to the emerging paradigm of big data computing and the increasing role of the underpinning technologies in organizing, planning, and designing sustainable urban forms. The intention is to utilize and apply well–informed, knowledge–driven decision–making and enhanced insights to improve and optimize urban operations, functions, services, designs, strategies, and policies in line with the long–term goals of sustainability. The authors argue that there is tremendous potential for advancing sustainable urbanism and transforming the knowledge of sustainable urban forms through creating a data deluge that can, through analytics, provide much more sophisticated, finer–grained, wider–scale, real–time understanding and control of various aspects of urbanity in the undoubtedly upcoming Zettabyte Age.

4.7.2. The unfolding era of data–Driven smart sustainable urbanism

All the arguments, opportunities, and prospects presented and discussed above are rather part of the ongoing debate on integrating sustainable cities and smart cities. The rationale for this amalgamation is that sustainable urban forms have been problematic, whether in theory or practice, so is yet knowing to what extent progress has been made towards sustainable cities (Bibri and Krogstie, 2019b). And as such forms are associated with a number of problems, issues, and challenges, to reiterate, much more needs to be done considering the very fragmented, conflicting picture that arises of change on the ground in the face of the expanding urbanization and the scarcity of resources. The current deficiencies, limitations, fallacies, and uncertainties concern the planning, design, and development of compact cities in the context of sustainability (e.g., Bibri and Krogstie, 2017a, 2020; Breheny, 1992, 1996; Dempsey and Jenks, 2010; De Roo, 2000; Hofstad, 2012; Jabareen, 2006; Lim and Kain, 2016; Neuman, 2005; Williams, 2010). They largely involve the question of how sustainable urban forms should be monitored, understood, and analyzed so as to improve, advance, and maintain their contribution to the goals of sustainable development (Bibri and Krogstie, 2019a, b). The underlying argument is that more innovative solutions and sophisticated approaches are needed to overcome the kind of wicked problems, unsettled issues, and complex challenges pertaining to such forms with respect to urbanism practices, strategies, and approaches. This bring us to the issue of sustainable cities and smart cities being extremely fragmented as landscapes and weakly connected as approaches (e.g., Angelidou et al., 2017; Bibri, 2019a, b, 2020; Bibri and Krogstie, 2019a, b; Bifulco et al., 2016; Kramers et al., 2014), despite the proven role of advanced ICT and the untapped potential of big data technologies and their novel applications for advancing sustainability under what is labeled 'smart sustainable cities' (Bibri, 2018b, 2019a, c; Bibri and Krogstie, 2017b; Kramers et al., 2016).

In light of the above, a recent research wave has started to focus on smartening up sustainable urban forms, which revolves particularly around amalgamating the landscapes of and the approaches to sustainable cities and smart cities in a variety of ways in the hopes of reaching the optimal level of sustainability (Bibri and Krogstie, 2019a, b). This integrated approach: smart sustainable urban forms, tends to take several forms in terms of combining the strengths of sustainable cities and smart cities based on how the integration as an idea can be conceptualized and operationalized. As a corollary of this, there is a host of unexplored opportunities towards new approaches to smart sustainable urban planning and developnent as an attempt to mitigate or overcome the extreme fragmentation of and weak connection between the landscapes and approaches of sustainable cities and smart cities (Angelidou et al., 2017; Bibri and Krogstie, 2019a, b, 2020), respectively.

However, research on the uses of big data in relation to sustainable urban development tends to be scant. This paucity of research can be explained by the fact that smart sustainable cities are a new urban phenomenon and only became widespread during the mid 2010s (Bibri and Krogstie, 2017a). In their article 'Enhancing sustainable urban development through smart city applications', Angelidou et al. (2017) analyze comparatively a total of 32 smart city applications that can be found in the Intelligent Cities Open Source (ICOS) community repository. The authors classify the applications according to, among other criteria, the environmental issue they address, namely high traffic density, high amount of waste, increasing air pollution, increasing energy consumption/sinking resources, loss of biodiversity and natural habitat, and sinking water resources. However, they neither specify, or provide any detail on, which of these applications, and how they, relate to big data analytics. Gebresselassie and Sanchez (2018) ask, in their recent study on smart tools for socially sustainable transport, how smartphone applications (apps) can address social sustainability challenges in urban transport, if at all, with a particular focus on transport disadvantages experienced by citizens due to low income, physical disability, and language barriers and based on a review of 60 apps. This study reveals that transport apps have the potential to address or respond to the equity and inclusion challenges of social sustainability by employing universal design in general–use apps, including cost–conscious features and providing language options, as well as by specifically developing smartphone apps for persons with disabilities. The outcome of this study adds a new dimension to the compact city as to strengthening its social sustainability goals. However, while this is not to imply that such apps are a panacea for the equity and inclusion issues related to urban transport—but only one of the tools that can be used to address them, there nevertheless are other urban domains where new apps of similar use need to be developed and mainstreamed to address the same issues, including healthcare, education, and public and social services, and so on. Moreover, while this study brings the social aspects of sustainability to the forefront, and helps to gain a better understanding of the application of smart tools for socially sustainable transport, there is no mention of the role of big data analytics in the functioning of such apps, or how they relate to it at all, despite the mention of some articles that in fact address big data analytics and its applications in smart cities in terms of the new smart applications proliferating urban transportation systems. Indeed, their operation must be based on big data on travel behaviour, mobility models, and multimodal transport. See Batty et al. (2012) and Batty (2013) for examples of such operation, indeed.

Remaining on the same topic, contending that topical studies largely ignore the role of the IoT and related big data applications in improving environmental sustainability in the context of smart sustainable cities, Bibri (2018b) reviews and synthesizes the relevant literature with the objective of identifying the state-of-the-art sensor-based big data applications enabled by the IoT for environmental sustainability and related data processing platforms and computing models, and further explores the opportunity of augmenting the informational landscape of sustainable urban forms with big data applications to achieve the required level of environmental sustainability. To extend this work, while maintaining this time that topical studies tend to deal mostly with data–driven smart urbanism while barely exploring how this approach can improve and advance sustainable urbanism under what is labeled 'data–driven smart sustainable cities,' Bibri (2019c) examines how data–driven smart sustainable cities are being instrumented, datafied, and computerized so as to improve, advance, and maintain their contribution to the goals of sustainable development through more enhanced urban practices and optimized urban processes; proposes, illustrates, and describes a novel architecture and typology of data–driven smart sustainable cities; and highlights and substantiates the great potential of big data technology for enabling such contribution by identifying, synthesizing, distilling, and enumerating the key practical and analytical applications of this advanced technology in relation to multiple urban systems and domains. These specifically include—with respect to operations, functions, services, designs, strategies, and policies—transport and traffic, mobility, energy, power grid, environment, buildings, infrastructures, urban planning, urban design, governance, healthcare, education, public safety, and academic and scientific research. The author argues that smart sustainable cities are becoming knowable, controllable, and tractable in new dynamic ways thanks to urban science, responsive to the data generated about their systems and domains by reacting to the analytical outcome of many aspects of urbanity in terms of optimizing and enhancing operational functioning, management, planning, design, development, and governance in line with the goals of sustainable development.

4.7.3. The role and potential of big data technology for the compact city: planning, design, and operational functioning

The link between big data technology and the compact city pertains to the contribution of the former to enhancing and advancing the planning and design approaches and monitoring and optimizing the operational functioning of the latter. Table 4 attempts to capture the core of this link.

4.7.4. Discussion of issues related to science, technology, and society

Visions of future advances in science and technology (S&T), predominately computing and ICT, inevitably bring with them wide–-ranging common visions on how societies, and thus cities as social organizations, will evolve in the future as well as the immense opportunities this future will bring (Bibri, 2019f, 2020; Bibri and Krogstie, 2016). This relates to the role of science–based technology in modern society in terms of its progress, a half–a–century debate within which the assumptions and claims made in the preceding discussion are positioned. The focus here is on the role of big data science and analytics and the underpinning technologies in advancing sustainability in modern cities. This form of S&T has recently permeated contemporary urban debates, policy, and politics in the sphere of smart sustainable urbanism. As s a new area of S&T, big data science and analytics embodies an unprecedentedly transformative power—which is manifested

Table 4
The role and potential of big data technology for the compact city.

The Role and Potential of Big Data Technology for Compact Cities
Planning
Enabling joined-up planning, a form of integration and coordination that allows system–wide effects of sustainability to be tracked, understood, analyzed, and built into the very designs and responses characterizing the operations and functions of the compact city, i.e., spatial patterns of physical objects, infrastructure, activities, and services as embedded in space and time.
Extensive interactions across many scales of the compact city as ICT is essentially network-based given its ubiquitous and constitutive nature. Data–driven approaches to integrating city systems, coordinating city domains, and coupling city networks is essential to efficient land use planning and development, resource optimization, and cost reduction.
The provision of urban data from the functions associated with compact city designs offers the opportunity for a continuously integrated view or synoptic intelligence pertaining to the effects of the way the compact city is functioning in real time. Datasets imply, in addition to showing immediately such functioning, how long term changes can be detected.
Aggregating real-time data to deal with changes in the compact city at any scale and over any time period. They can be used to make the compact city more sustainable over different spatial and temporal scales, yielding opportunities for solving complex problems
Planning across multiple time scales in order to increase the contribution of the compact city to the goals of sustainable development in the long term by continuous reflection in the short term. Short–termism in compact city planning is about measuring, evaluating, modelling, and simulating what takes place in the city over hours, days, or months instead of years or decades. In this context, big data can be used to derive new theories of how the compact city functions in ways that focus on much shorter term issues than hitherto, and much more on mobility and movement than on the long–term functioning of the compact city as a complex system.
Continuous planning as data constantly flood from urban systems and domains and are updated in real time, thereby allowing for a dynamic conception of the planning, instead of a static conception of the planning, of the compact city. This implies conceiving the compact city in terms of processual outcomes of urbanization as regards building and living processes, as well as consumption and production levels, rather than conceiving it in terms of form.
Weaving urban intelligence and planning functions into the fabric of the institutions of the compact city whose mandate is making urban living more environmentally, economically, and socially sustainable.
Urban intelligence functions enable new approaches into how the compact city functions and utilizes and integrates complexity science, urban science, and big data science in fashioning new powerful forms of urban simulations models and optimization and prediction methods that can generate city structures and forms that improve sustainability, efficiency, equity, and the quality of life for citizenry.
Maximizing the use of data to encourage the compact city developers to adopt a more consistent approach to deploying digital infrastructure to future proof new developments and transformations associated with urban intensification as a major strategy of compactness.
Design
Using advanced simulation models for assessing and optimizing the designs of the compact city in terms of scalability and flexibility in ways that respond to urban growth, environmental pressures, changes in socio–economic needs, and discontinuities.
The real time compact city and its ubiquitous sensing providing information about longer term changes enables constructing urban simulation models to inform future designs thanks to the disaggregate models. This involves exploring many different kinds of models that extend complexity science and advance urban science as informed by big data science and analytics. This is of significance to understanding and dealing with the wicked problems the compact city inherently embodies.
Providing effective ways to identify the macroscopic observables and control parameters that influence individual decisions in the compact city, and then integrating them in agent–based simulation models based on the large number and variety of trajectories of citizens in different locations.
Monitoring, analyzing, and evaluating the environmental, economic, and social performance of the design strategies of the compact city as regards the extent to which they contribute to the goals of sustainable development based on different scenarios and situations.
Effective analysis and deep understanding of the relationship between individual and collective mobility and the environmental, economic, and social effects that are assumed to be produced by the design strategies of the compact city.
Enhancing the performance of the design strategies of the compact city through augmenting them with data-driven technology solutions, or improving their integration in relation to multiple spatial scales as outcomes of processes enabled by ICT.
Predicting socio − economic and demographic changes and devising more integrated design strategies as to the urban and technological components of the compact city.
Operational Functioning
Developing intelligence functions in the form of urban operating and innovation centers based on how the compact city is performing and changing in its nature in light of its real-time operational functioning.
The linking and integration of diverse forms of urban data from various urban domains provide a more holistic analysis, which in turn makes it possible to control, manage, and regulate urban life by analyzing, harnessing, and translating contextual and actionable data into more efficient operational functioning processes.
Relating the compact city spatial organizations, spatial scales, and infrastructures to their operational functioning through control, automation, optimization, and management.
Improving participation, equity, fairness, safety, and accessibility, as well as service delivery in relation to the quality of life. These are associated with attractiveness enabled by multidimensional mixed land use.
Enhancing and optimizing the transport of energy, water, materials, products, and people already minimized by compactness.
Calculating and analyzing the costs and environmental impacts of the transportation choices of people, combining all modes of transit. Equipping public transport with GPS sensors to monitor movement.
Addressing equity and inclusion issues in urban transport using smartphone apps and thus creating socially sustainable urban transport.
Enhancing transportation system efficiency by influencing personal travel behavior decisions using advanced platforms and smartphone apps. Use of information on passengers travelling for planning of new routes and road infrastructure.
Providing visibility into transit system performance based on cloud–based solution, and helping the compact city makes better decisions about transportation by combining the IoT–based generated big data and spatial analytics.
Managing mobility in public transport in terms of keeping the interaction between businesses, universities, and citizens as to how they should make the choice of travel modes for the everyday needs and what can be done to make travel behavior more sustainable.
Managing all services of the transport complex of the compact city on the basis of data received by the situation center.
The collection and analysis of information on the movement of citizens on transport maps operators to determine the necessity of the launch of new public transport routes.
The use of a smart traffic light system for determining the movement of priorities of different types of transport.

not only in the form of revolutionizing science and transforming knowledge, but also in advancing social practices, catalyzing major shifts, and fostering societal transitions (Bibri, 2019e). Of particular relevance, it is instigating a massive change in the way sustainable cities and smart cities are understood, studied, planned, designed, and managed (Bibri, 2018a, b, 2019a, 2020; Kitchin, 2014a, b, 2015a, b, 2016) so as to improve, advance, and maintain their contribution to the goals of sustainable development in the face of the expanding urbanization. This relates to what has been dubbed data–driven smart sustainable urbanism, a new era which is presently unfolding wherein smart sustainable urban practices and processes are becoming highly responsive to a form of data–driven urbanism. 'At the heart of data–-driven urbanism is a computational understanding of city systems that reduces urban life to logic and calculative rules and procedures, which is underpinned by a…realist epistemology. This epistemology is informed by and sustains urban science…, which seeks to make cities more knowable and controllable' (Kitchin, 2016a, p. 2).

However, as there is a little understanding about how data–driven smart sustainable urbanism has emerged and why it has become institutionalized and interwoven with politics and policy—urban dissemination, Bibri (2019f) has recently conducted a study in science, technology, and society (STS), where he examines the intertwined societal factors underlying its materialization, success, expansion, and evolution, and further critically discusses urban science and big data technology as social constructions in terms of their inherent flaws, limits, and biases. The author concludes that data–driven smart sustainable urbanism is shaped by socio–cultural and politico–institutional structures, and will prevail for many years to come given the underlying transformational power of big data science and analytics, coupled with its legitimation capacity associated with the scientific discourse as the ultimate form of rational thought and the basis for legitimacy in knowledge–making and policy–making. However, as the author asserts, there is a need for re–casting urban science in ways that reconfigure the underlying epistemology to recognize the complex and dynamic nature of smart sustainable cities, as well as for re–casting them in ways that re-orientate in how they are conceived.

Furthermore, big data science and analytics as a form of S&T and its role in advancing sustainable urbanism has been questioned and criticized by several scholars, often exposing the risks and drawbacks of the so–called techno–scientific achievements. In general, Huesemann and Huesemann (2011) demonstrate that technological optimism is grounded in ignorance, leading to uncritical acceptance and adoption of new technologies. In particular, Cowley (2016) contends that smart city and eco-city visions and plans are often criticized for paying insufficient attention to the social and political dimensions of real urban space, pointing to an underlying utopianism. On this critical view, the author adds, not only are such visions and plans unable to live up to their own utopian promises, but also even covertly reproduce the structural conditions of unsustainability. To elaborate further on this, 'it seems tempting to advocate that critics should seek to debunk this [utopian] rhetoric, in order to reveal the contingent political and economic agendas which it conceals. Thinking actively about the SF [science fiction] dimensions of the smart-eco city may, in other words, be one way of allowing more fundamental questions to surface, related to its ability to deliver more than unsustainable business as usual' (Cowley, 2016, p. 11).

With respect to the social and political consequences, Kitchin (2014) provides a critical reflection on the implications of data–driven smart urbanism, examining five emerging concerns: the politics of big urban data; technocratic governance and city development; corporatization of city governance and technological lock–ins; buggy, brittle and hack–-able cities; and the panoptic city. A large part of this examination constitutes also the aim of Kitchin's (2015) paper, which indeed provides a critical overview of data–driven, networked urbanism, focusing in particular on the relationship between data and the city, and critically examines a number of urban data issues, including corporatization, ownership, control, privacy and security, anticipatory governance, and challenges. In addition, Kitchin (2016) examines the forms, practices, and ethics of smart urbanism and urban science, paying particular attention to privacy, dataveillance and geosurveillance; and data uses, such as social sorting and anticipatory governance, among others.

Besides, the rising demand for big data computing and the underlying enabling technologies, coupled with the growing awareness of the associated potential to transform the way smart sustainable cities can function with respect to planning and development, comes with major challenges related to the design, engineering, development, implementation, and maintenance of data–driven applications. The challenges are mostly computational, analytical, and technical in nature (Table 5), and sometimes logistic in terms of the detailed organization and implementation of the complex technical operations involving the installation and deployment of the big data ecosystem and its components.

For a detailed list and discussion of such challenges, the interested reader can be directed to Bibri (2019b). Adding to the above primarily technological challenges are the financial, organizational, institutional, cultural, regulatory, and ethical ones, which are associated with the implementation, retention, and dissemination of big data across urban domains. As an example, ethical controversies over the benefits of big data analytics and its applications involve limited access and related digital divides and other concerns about accessibility.

Table 5
Computational, analytical, technical, and logistic challenges.

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

5. Conclusions

Compact city planning and development has long been the preferred response to the challenges of sustainable development. Much of the discourse about the compact city constructs it as a model that secures environmentally sound, economically viable, and socially beneficial development through dense, intense, diverse, and mixed use patterns that rely on sustainable transportation and promote green space. Therefore, global urban policies promote the concept of the compact city as a response to environmental integration, economic development, and social justice, as well as attractiveness.

This paper provided a comprehensive state–of–the–art review of compact urbanism as a set of planning and development practices and strategies, focusing on the three dimensions of sustainability and the significant, yet untapped, potential of big data technology for enhancing such practices and strategies under what is labelled 'data–driven smart sustainable urban form.

This paper identified compactness, density, diversity, mixed land use, sustainable transportation, and green space as the prevalent design principles and strategies underlying the compact city as applied and pursued in urban planning and development. At the core of the compact city is, as this paper demonstrated, the clear synergy between the underlying principles and strategies in terms of their cooperation to produce combined effects greater than the sum of their separate effects with respect to the benefits of sustainability as to its tripartite composition. Indeed, they are not mutually exclusive and thus must take place or exist at the same time in order to guarantee the viability and sustain the performance of the compact city regarding its contribution to the three goals of sustainable development. For example, urban greening enhances the presence of the compact city ideas in the urban areas that are targeted by development strategies (Bibri et al., 2020). Also, the availability and quality of the public transport infrastructure is a determinant factor for stimulating urban development projects and initiatives pertaining to compactness in the nodes and built–up areas so as to boost the benefits of sustainability (Bibri et al., 2020; Hofstad, 2012). In general, urban planning and development policies are supported by the proponents of the agglomeration effects (Glaeser, 2011) rendered by the proximity and connectivity of diverse urban components, leading to density, diversity, and mixed land use (Lim and gain 2016) that must rest on sustainable transportation (Dempsey, 2010; Jenks and Jones, 2010).

Furthermore, this paper corroborated that the compact city is justified by its ability to contribute to the environmental, economic, and social goals of sustainable development. Compact cities are endorsed as a response to critical environmental, economic, and social challenges by turning cities more efficient, equitable, livable, vibrant, and attractive. To put it differently, agglomeration, proximity, and diversity have been demonstrated to promote environmental quality, social equity, accessibility, life quality, innovation, economic viability, and rural land and natural area protection. However, the economic goals seem to dominate over the environmental and social goals, notwithstanding the general claim about the three dimensions of sustainability being equally important and mutually dependent. The main issues identified in this regard include socio–economic segregation, social inequity, noise pollution, and green space loss. Compact cities involve tensions and dilemmas when attempting to balance between the goals of sustainable development. This continues to stimulate more endeavors towards finding more effective ways to enhance and advance this advocated urban model.

The conflicting and contentious issues pertaining to the compact city model arguably relate more or less to the debate between the 'decentrists', who are in favour of a decentralized form, and the 'centrists', who are in favour of a high-density compact form. Of particular relevance in this respect, the decentrists are skeptical on the environmental benefits delivered by the strategy; claim that the expected energy reduction is modest compared to the discomfort caused by the necessary rigorous policies; and believe that it is impossible to halt the urban decentralisation phenomenon that fits the attitudes of the major part of the population. In addition, those issues are still largely associated with the whereabouts of the compact city as to its implementation and development, and what types of planning approaches are adopted to promote dense and diverse urban patterns.

In addition, with its several dimensions working together synergistically, the compact city is a very complex urban model. This explains the kind of the wicked problems it embodies in terms of urban planning and development, which in turn justifies the kind of problems, issues, and challenges it is associated with.This pertains mostly to the question of how sustainable urban forms should be monitored, understood, analyzed, and thus planned and designed so as to improve, advance, and maintain their contribution to the goals of sustainable development. This brings us to the issue of sustainable cities and smart cities being extremely fragmented as landscapes and weakly connected as approaches to urbanism, despite the proven role of advanced ICT in and the tremendous, untapped potential of big data science and analytics and the underpinning technologies for advancing sustainability under what is labeled 'smart sustainable cities'. Indeed, big data technologies have become essential to the functioning of both smart cities and sustainable cities. Consequently, their practices and processes are becoming highly responsive to a form of data-driven urbanism. In more detail, 'we are moving into an era where instrumentation, datafication, and computerization are routinely pervading the very fabric of cities, coupled with the…integration and coordination of their systems and domains. As a result, vast troves of data are generated, harnesses, analysed, and exploited to control, manage, organize, and regulate urban life… This data-driven approach to urbanism is increasingly becoming the mode of production for smart sustainable cities.' (Bibri, 2019c, p. 1) Of more relevance, a new era is presently unfolding wherein sustainable urbanism is increasingly becoming smart data-driven.

Huge advances in some areas of knowledge about urban sustainability and a multitude of exemplary practical initiatives have been realized, thereby raising the profile of sustainable urban forms worldwide. The change is still inspiring and the challenge continues to induce scholars and practitioners to further enhance the compact city model as regards design practices, as well as to integrate it with other models of sustainable urban form given their common goal of, and clear synergy in, contributing to sustainable development. As concluded by Jabareen (2006, p. 48), 'different planners and scholars may develop different combinations of design concepts to achieve sustainable development goals… However, all should be forms that environmentally contribute beneficially to the planet for the present and future generations.' In that respect, more in–depth knowledge on planning practices is needed to capture the vision of sustainable urban development, so too is a deeper understanding of the multi–faceted processes of change to achieve sustainable urban forms. This entails conceptualizing multiple pathways towards attaining this vision and developing a deeper understanding of the interplay between social and technical solutions for sustainable urban forms (Williams et al., 2000), especially those involving engineering and applied sciences related to big data science and analytics and the underpinning technologies.

Concerning the value of this review, it resides in enabling researchers and scholars to focus their work on the identified real–world problems, issues, and challenges pertaining to the compact city, in particular, and to the sustainable city, in general, as well as on the existing knowledge gaps in the field of sustainable urbanism. Such focus entails creating and exploring new research opportunities to enhance and advance the practices and processes of such urbanism, especially through embracing and leveraging what big data science and analytics has to offer in this regard. Practitioners and experts can make use of the outcome to identify the common weaknesses of the compact city as a model of sustainable urbanism and to find more effective ways to solve them in light of the emerging paradigm of data–driven smart sustainable urbanism..

I hope that this paper will provide the grounding for further in–-depth research on the compact city as the leading paradigm of sustainable urbanism, especially in relation to its data–driven smart dimension. I would like particularly to encourage applied theoretical and empirical investigations to illuminate the design principles, planning practices, and development strategies underlying the compact city model and the assumptions behind related initiatives. And hence the claims that this model can make urban living more sustainable and the role of advanced ICT in supporting this goal. The rationale for this is that as the demand for applied theoretical and practical ideas about how to achieve the required or optimal level of sustainability through compact urbanism increases, these initiatives are likely to get increasing attention from policymakers and practitioners around the world. Further research should focus on providing the knowledge that these actors will need to make informed decisions about how to achieve the status and thus objectives of the compact city towards achieving a sustainable city. In addition, this paper stimulates further discussion to debate over the disruptive, synergetic, and transformational effects of big data science and analytics on compact urbanism. It also encourages more critical analysis focused on establishing, uncovering, substantiating, challenging, and/or questioning the assumptions behind the real potential of advanced ICT for advancing sustainability.

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