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REVIEW

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The core academic and scientific disciplines underlying data-driven smart sustainable urbanism: an interdisciplinary and transdisciplinary framework

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Abstract

A new era is presently unfolding wherein both smart urbanism and sustainable urbanism processes and practices are becoming highly responsive to a form of data-driven urbanism under what has to be identified as data-driven smart sustainable urbanism. This flourishing field of research is profoundly interdisciplinary and transdisciplinary in nature. It operates out of the understanding that advances in knowledge necessitate pursuing multifaceted questions that can only be resolved from the vantage point of interdisciplinarity and transdisciplinarity. This implies that the research problems within the field of data-driven smart sustainable urbanism are inherently too complex and dynamic to be addressed by single disciplines. As this field is not a specific direction of research, it does not have a unitary disciplinary framework in terms of a uniform set of the academic and scientific disciplines from which the underlying theories can be drawn. These theories constitute a unified foundation for the practice of data-driven smart sustainable urbanism. Therefore, it is of significant importance to develop an interdisciplinary and transdisciplinary framework. With that in regard, this paper identifies, describes, discusses, evaluates, and thematically organizes the core academic and scientific disciplines underlying the field of data-driven smart sustainable urbanism. This work provides an important lens through which to understand the set of established and emerging disciplines that have high integration, fusion, and application potential for informing the processes and practices of data-driven smart sustainable urbanism. As such, it provides fertile insights into the core foundational principles of data-driven smart sustainable urbanism as an applied domain in terms of its scientific, technological, and computational strands. The novelty of the proposed framework lies in its original contribution to the body of foundational knowledge of an emerging field of urban planning and development.

Keywords: Data-driven smart sustainable urbanism, Smart urbanism, Sustainable urbanism, Scientific disciplines, Academic disciplines, Urban science, Data-intensive science, Sustainability, Big data analytics

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1 Introduction

A new era is presently unfolding wherein both sustainable urbanism and smart urbanism processes and practices are being highly responsive to a form of data-driven urbanism. In this light, there has recently been a conscious push for smart cities and sustainable cities across the globe to be smarter and thus more sustainable by developing and implementing data-driven technology solutions in relation to various urban systems and domains to enhance and optimize their operations, functions, services, designs, strategies, and policies. Big data technologies have become as essential to the functioning of smart cities (e.g., Batty, 2013; Kitchin, 2014, 2015, 2016; Kitchin, Lauriault, & McArdle, 2015; Marvin, Luque-Ayala, & McFarlane, 2016) as to that of sustainable cities (e.g., Bibri, 2019a, b, 2020b; Bibri & Krogstie, 2020a, b, c; Pasichnyi et al., 2019; Shahrokni, Levihn, & Brandt, 2014; Shahrokni et al., 2014; Shahrokni, Lazarevic, & Brandt, 2015; Shahrokni et al., 2015; Thornbush & Golubchikov, 2019). They are also being used in smart cities to improve sustainability (e.g., Petrovic and Kocic 2020; Angelidou et al., 2017; Batty et al., 2012; Bettencourt, 2014; Bibri, 2019c; Eden Strategy Institute, 2018; Kumar & Prakash, 2016; Nikitin, Lantsev, Nugaev, & Yakovleva, 2016). Consequently, we are moving into an era where instrumentation, datafication, and computation are routinely pervading the very fabric of both sustainable cities and smart cities. One of the consequences of data-driven smart sustainable urbanism is that city systems are becoming much more tightly interlinked and integrated. As a result, vast troves of data are being generated, analyzed, harnessed, and exploited to control, manage, and regulate urban life based on innovative planning approaches, enabled by data-driven smart technologies.

Numerous city projects, programs, and initiatives, both within the ecologically and technologically advanced nations, are shifting from merely focusing on the application of sustainability knowledge to city planning and design in the framework of sustainable cities and from the development and implementation of new technologies in city management in the framework of smart cities to the integration of sustainability and smartness at the technical and policy levels. Smart cities are increasingly connecting the ICT infrastructure, the physical infrastructure, the social infrastructure, and the economic infrastructure to leverage their collective intelligence in a way to become more efficient, sustainable, resilient, livable, and equitable. As such, they seek to solve a fundamental conundrum—ensure economic development, social equity, and the quality of life at the same time as optimizing energy efficiency, mitigating pollution, and strengthening infrastructure resilience. This has been made possible by utilizing the fast–flowing torrent of data and the rapidly evolving core enabling and driving technologies of the IoT and big data analytics as emerging computing paradigms. In particular, the generation of data and the advancement of computational/analytics techniques for monitoring, understanding, analyzing, and planning the city are the most significant strengths of smart cities that are being increasingly embraced and leveraged by sustainable cities in order to improve and advance their contribution to sustainability. For supra–national states, governments, and city officials, smart cities offer the enticing potential of environmental improvement and socio–economic development, as well as the renewal of urban centers as hubs of innovation and research (e.g., Bibri & Krogstie, 2020a, b, c; Kitchin, 2014, 2016; Mora & Bolici, 2016; Nikitin et al., 2016; Noori, Hoppe, & de Jong, 2020; Townsend, 2013).

However, the field of data-driven smart sustainable urbanism does not have a unitary disciplinary framework in terms of a uniform set of the academic and scientific disciplines from which the underlying theories can be drawn. These theories constitute a unified foundation for the practice of data-driven smart sustainable urbanism. Data-driven smart sustainable urbanism as a form of practice is underpinned by complex interdisciplinary and transdisciplinary knowledge. In more detail, as a holistic approach, it involves a range of theories and related approaches as well as scientific and technological foundations drawn from a variety of academic and scientific disciplines. Theories represent the body of scientific concepts, definitions, relationships, and assumptions that describe and explain the data-driven smart sustainable city formation phenomenon, or define the body of knowledge of this emerging paradigm of urbanism. They include, but are not limited to, urban development, urban planning, urban systems, urban design, urban policy, urban resilience, urban sustainability, urban morphology, urban complexity, systems thinking, action net theory, actor network, urban spatial analysis, economics, urban dynamics, urban computing, and urban modelling. They are fundamental in guiding research and practice within the field of data-driven smart sustainable urbanism. In this respect, they can be drawn from different city-related disciplines for the purpose of their integration and/or fusion to address complex topics or problems within different research areas. The research outcome can enhance, extend, advance, and/or challenge the existing body of knowledge of the prevailing and emerging paradigms of urbanism in the light of new paradigmatic or epistemological shifts, such as data-intensive science, or global trends, such as urbanization, all in the context of sustainability.

Interdisciplinarity and transdisciplinarity have become a widespread mantra for research within diverse fields, accompanied by a growing body of scholarly publications. The research field of data-driven smart sustainable urbanism is profoundly interdisciplinary and transdisciplinary in nature. It operates out of the understanding that advances in knowledge necessitate pursuing multifaceted questions that can only be resolved from the vantage point of interdisciplinarity and transdisciplinarity. This in turn implies that the research problems within this field are inherently too complex and dynamic to be addressed by single disciplines. Interdisciplinarity relates to the world's most pressing and challenging problems with long-term wide-area impacts. Data-driven smart sustainable urbanism requires understanding diverse academic and scientific disciplines and how these can interrelate to solve similar problems. Accordingly, interdisciplinarity can be best applied to complex topics that can only be understood by interrelating the perspectives of diverse disciplines. Seeking to provide a holistic understanding of the topic of data-driven smart sustainable urbanism for the common purpose of policy or in the pursuit of normative actions, the interdisciplinary approach to research insists on mixing disciplines. It crosses boundaries between different disciplines to create new perspectives and insights on the basis of interactional knowledge beyond these disciplines. Its strength lies in the ability of interlinking different analyzes, using insights and methods from different disciplines in parallel—not in conjunction, and spilling over disciplinary boundaries. The interdisciplinary perspective of the disciplinary framework that this paper is concerned with is a topical and organizational unit that is determined by the nature of the research field of data-driven smart sustainable urbanism.

The transdisciplinary approach to research insists on fusing, rather than mixing, different disciplines and hence using insights and methods from in conjunction—with a result that exceeds the simple sum of each. Transdiciplinarity lends itself readily to the exploration of complex problems. It concerns that which is at once between, across, and beyond single disciplines. Its aim is to understand present phenomena in the world, of which a key imperative is the overarching unity of knowledge. Thus, understanding the tenets, and setting side-by-side elements, of pertinent theories that have clear implications for the notion of data-driven smart sustainable cities permits a complete understanding of its topic. From a general perspective, transdisciplinary research entails efforts made in light of different academic and scientific disciplines in a joint endeavor to innovate in creating new conceptual, theoretical, and methodological approaches that move beyond discipline–specific perspectives to address and overcome a common problem. The transdisciplinary perspective of the disciplinary approach that this paper is concerned with is, in addition to being a topical and organizational unit determined by the nature of the research field of data-driven smart sustainable urbanism, an opportunity to situate the researcher in an ecology of ideas, a process which can be approached from the perspective of complexity. In this respect, the key dimensions that can be considered include: integrating rather than eliminating the researcher from the research, meta–paradigmatic rather than intra–paradigmatic, research–grounded rather than discipline–grounded, and applying systems and complexity thinking rather than reductionism.

In light of the above, it is of significant importance to develop an interdisciplinary and transdisciplinary framework. With that in regard, this paper identifies, describes, discusses, evaluates, and thematically organizes the core academic and scientific disciplines underlying the field of data-driven smart sustainable urbanism. In terms of the eligibility criteria for selection, the focus is on those academic and scientific disciplines that are concerned with he core theoretical underpinnings of the study being carried out. This study aims to analyze, investigate, and develop a novel model for data-driven smart sustainable cities of the future as a strategic planning process of transformative change towards sustainability. This is grounded in the amalgamation of the four case studies conducted on (1) compact cities (Bibri, Krogstie, & Kärrholm, 2020), (2) eco-cities (Bibri & Krogstie, 2020a), (3) data–driven smart cities (Bibri & Krogstie, 2020b), and (4) environmentally data-driven smart sustainable cities (Bibri & Krogstie, 2020c) in terms of their dimensions, strategies, and solutions. These have been integrated into a framework for strategic sustainable urban development planning to guide the process of building the novel model for data-driven smart sustainable cities of the future (Bibri & Krogstie, 2020d). The preliminary selection of the academic and scientific disciplines was done in accordance with the problem under investigation: How to improve and advance the contribution of sustainable cities to the goals of sustainability with the support of the data-driven technologies and solutions being offered by smart cities? With that in mind, for a given discipline to be considered in terms of its potential to provide any information of pertinence, it should relate to one of the conceptual and theoretical subjects specified in the futures study and related case studies. The emphasis was placed on the disciplines that provided primary information, especially from cross–domain analysis and cross-disciplinary perspective. On the whole, scoring the disciplines was based on the inclusion of the foundational principles of the processes and practices of data-driven smart sustainable urbanism in terms of how it was approached. Conversely, the disciplines excluded were those that did not meet the specific criteria with respect to their relevance accordingly.

The remainder of this paper is organized as follows: Section 2 briefly introduces and discusses some of the previously proposed approaches and models of sustainable cities and smart cities. Section 3 introduces, describes, and discusses the key established and emerging academic disciplines underlying the field of data-driven smart sustainable urbanism. Section 4 introduces, describes, and discusses the key established and emerging scientific disciplines underlying the field of data-driven smart sustainable urbanism. This paper ends, in Section 5, with concluding remarks together with an interdisciplinary and transdisciplinary framework for the core academic and scientific disciplines underlying data-driven smart sustainable urbanism.

2 Related work: sustainable city and smart city approaches and models

Since the main objective of this study is to "develop a novel model for data-driven smart sustainable urbanism, " reviewing existing approaches and models of sustainable urbanism and smart urbanism is deemed useful and pertinent in terms of contextualizing this study and helping readers to understand the unique contribution and novelty of the new model for data-driven smart sustainable urbanism.

Sustainable cities have, over the last four decades or, been the leading global paradigm of urbanism thanks to the models of sustainable urban form proposed as new frameworks for redesigning and restructuring urban places to make urban living more sustainable. There are different approaches to sustainable cities, which tend to be identified as models of sustainable urban form. These include compact cities, eco–cities, new urbanism, urban containment (Jabareen, 2006) landscape ecological urbanism (landscape architecture and urban ecology (Kuitert, 2013; Steiner, 2011), and so on. Compact cities and eco-cities are the central paradigms of sustainable urbanism and the most advocated models of sustainable urban form. Williams, Burton, and Jenks (2000, p. 355) conclude that sustainable urban forms are "characterized by compactness (in various forms), mix of uses and interconnected street layouts, supported by strong public transport networks, environmental controls and high standards of urban management." This characterization implies more or less a combination of the dimensions of compact cities and eco–cities. However, management tends to dominate within the eco–city, unlike the compact city where design is at the core of compaction strategies (Bibri, 2020b, c). The eco-city is about how the urban landscape is organized and steered (see, e.g., Jabareen, 2006; Kramers, Wangel, & Höjer, 2016) rather than the spatial pattern of the characteristic physical objects in the city. In fact, these two models of sustainable urban form share several concepts, ideas, and visions, though with some distinctive concepts and key differences as well. In this regard, according to Roseland (1997) and Harvey (2011), a desirable eco–city has a well–designed urban layout that promotes walkability, biking, and the use of public transportation system; ensures decent and affordable housing for all socio–economic and ethic groups; and supports future expansion and progress over time. These dimensions are at the heart of the compact city in terms of sustainable transportation and mixed land use strategies.

There seems to be a general consensus on the common dimensions of the compact city, whereas the idea of the eco–city is widely varied in conceptualization and operationalization. Indeed, there are many models of the eco–city according to an extensive literature review conducted by Bibri (2020b). These models can be caterogarized into three types: type 1 emphasizes passive solar design, type 2 combines passive solar design and greening, and type 3 focuses on green energy technologies and/or smart energy and environmental technologies.

A number of recent national and international policy reports and papers state that the models of the compact city and the eco-city contribute, though to varying degrees, to resource efficiency and reliability, environmental protection, socio-economic development, social cohesion and inclusion, quality of life and well-being, and cultural enhancement (Bibri, 2020b, c). It is argued that the compact city model is able to support and balance the three goals of sustainability (Burton, 2002; Hofstad, 2012; Jenks & Dempsey, 2005; Jenks & Jones, 2010), and that the eco–city model is able to achieve the goals of environmental sustainability together with some economic and social benefits of sustainability (Bibri & Krogstie, 2020a; Joss, 2010; Joss, Cowley, & Tomozeiu, 2013; Kenworthy, 2006; Mostafavi & Doherty, 2010; Rapoport & Vernay, 2011; Suzuki et al., 2010).

Transformative processes within sustainable cities have been in focus for some time now. The motivation for achieving the United Nations' Sustainable Development Goal (SGD) 11 has increased the need to understand, plan, and manage sustainable cities in new and innovative ways (United Nations, 2015a). In this regard, the United Nations's 2030 Agenda regards advanced ICT as a means to promote socio–economic development and protect the environment, increase resource efficiency, achieve human progress and knowledge in societies, upgrade legacy infrastructure, and retrofit industries based on sustainable design principles (United Nations, 2015b). This relates to the multifaceted potential of smart cities, which has been under study with respect to the role of big data technologies and their novel applications in strategic sustainable development within the framework of 2030 Agenda (United Nations, 2015c). However, as with sustainable cities, there are a number of approaches to smart cities (see Bibri, 2019c for a detailed review), as well as to smarter cities, including smart cities of the future (e.g., Batty et al., 2012), ubiquitous cities (e.g., Shin, 2009), ambient cities (e.g., Böhlen & Frei, 2009), sentient cities (e.g., Shepard, 2011; Thrift, 2014a), real-time cities (e.g., Kitchin, 2014), and data-driven cities (e.g., Bettencourt, 2014; Nikitin et al., 2016). The data-driven city is one of the recent faces of smarter cities.

The real challenge for the future lies in moving genuinely past the assumption that there are only two contrasting, mutually exclusive choices or realities: sustainable cities and smart cities. With an 'either/or' approach, there will not be much progress in sustainable urban development, as the huge challenges facing sustainable cities in such area as energy, environment, transport, and healthcare require an integrated approach to urbanism. The concept of smart sustainable cities has emerged as a result of three important global shifts at play today across the world, namely the diffusion of sustainability, the spread of urbanization, and the rise of ICT. This currently leading model of urbanism has materialized around the mid-2010s. Similarly, there are many approaches to smart sustainable cities apart from the data-driven approach as combined with the compact and ecological approaches, which is the main focus of this study. These approaches depend on the strategies that the cities badging or regenerating themselves as smart sustainable prioritize with respect to applied technology solutions and sustainability dimensions based on the kind of challenges they deal with (see, e.g., Al-Nasrawi, Adams, & El-Zaart, 2015; Bibri, 2018b; Kramers et al., 2016; Martin, Evans, & Karvonen, 2018; Noori et al., 2020; Pozdniakova, 2018; Seçkiner Bingöl, 2021).

3 Established and emerging academic disciplines or fields

An academic discipline or field is a branch of knowledge that is taught and researched as part of higher education. It involves research areas, research projects, research challenges, expertise, knowledge, scholars, communities, and studies as associated with a given scholastic subject area and related practice. Academic disciplines are particularly of usefulness for narrowing research efforts and creating ongoing dialogues about particular subjects. Thus far, there is no consensus on how some academic disciplines should be classified in relation the human, social, and natural sciences. City-related disciplines (urban planning, urban design, urban development, etc.) tend to be well-established and have branches, and these are often called subdisciplines. As such, they involve established knowledge directed for applied research within diverse domain applications. In the context of this paper, they provide a basis for data-driven smart sustainable urbanism as a collection of expert and scholarly knowledge, studies, research domains, practical methods, scholars, and practitioners.

3.1 Urban planning, design, and development

As a multifaceted process, urban planning focuses on the development, design, and regulation of land use and the built environment, including energy system, water system, waste system, sewage system, green and blue structure, as well as the infrastructure connecting urban areas at multiple levels, including transportation system, communication system, information system, and distribution network. This varied use of urban space focuses on the physical form, economic functions, and environmental and social impacts of the urban environment and on the location and intensity of different activities within it. Urban planning includes social science, architecture, human geography, politics, engineering, and design science.

As a governmental function, urban planning is practiced on the neighborhood, district, municipality, city, metropolitan, regional, and national scales. It has been approached from a variety of perspectives, often combined, including physical, spatial, geographical, ecological, technological, economic, social, cultural, and political. For what it touches on in terms of numerous city-life aspects, urban planning can be broadly categorized into different conceptual areas commonly referred to as types of urban planning, including:

- Strategic planning
- Sustainable planning
- Land-use planning
- Local planning
- Regional planning
- Master planning
- Environmental planning
- Infrastructure planning
- Urban revitalization
- Community economic development

This study is concerned with strategic planning and sustainable planning. Strategic planning entails setting high-level goals; formulating objectives and targets; arranging the means required for meeting them; and implementing, monitoring, steering, evaluating, and improving all the necessary steps in their proper sequence towards reaching the set goals. Sustainable planning is implemented in conjunction with compact and ecological designs and emphasizes the three dimensions of sustainability and their integration, while looking at how development interacts with the surrounding environment in a larger context. The primary goal of urban planning is to achieve the objectives of sustainable development in terms of mitigating the negative impacts on the environment through lowering energy usage, harvesting renewable sources, reducing material use, and minimizing waste, as well as in terms of improving social equity, human well–being, and the quality of life (Bibri 2021). Ultimately, it seeks to balance the conflicting demands of environmental sensitivity, economic development, social equity, and urban attractiveness and aesthetic appeal. This is at the core of urban sustainability, which represents an ideal outcome in the sum of all the goals of planning, on which there is widespread consensus with trade-offs and conflicts when it comes to decisions. Therefore, urban planning involves policy recommendations, public consultation, public administration, and implementation and management, as well as thorough research and in-depth analysis, and strategic thinking (Nigel 1998, 2007) to achieve the policy goals of sustainability.

Urban planning involves the application of scientific and technical processes in connection with different city-related components, such as land use, urban design, energy, transportation, waste, and infrastructure. It includes such techniques as modelling, simulation, prediction, geographic mapping and analysis, green condition monitoring, environmental monitoring, power and water supply analysis, transportation and traffic patterns recognition, energy demands and consumption patterns recognition, healthcare services allocation, land-use impacts analysis, and so forth. For example, Geographic Information Systems (GIS) can map the existing urban system and project the future impacts of changes on the environment and the economy. The idea of the data-driven smart sustainable city of the future is to obtain the right amount of data at the right place and from the right source to make well-informed, fact-based, strategic decisions with ease in relation to sustainability using most of these techniques. In this respect, it involves goal setting, data generation, processing, and analysis; modelling and simulation; design, as well as public consultation and citizen participation.

Urban design is an integral part of urban planning. It is concerned with planning, landscape architecture, and civil engineering, as well as sustainable design, ecological design, compact design, public design,and strategic design. Dealing with the design and management of the public domain and the way it is experienced and used by citizens, 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., Boeing, Church, Hubbard, Mickens, & Rudis, 2014; Larice & MacDonald, 2007). In this respect, it is about making connections between forms for human settlements and sustainable development in its tripartite composition.

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 the objectives and targets of sustainable development through design strategies and technology solutions, 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 rising socio–economic issues associated with the predominant paradigm of urban development by mitigating its negative impacts on the environment and improving social equity and human well–being. In short, sustainable urban development is a strategic approach to achieving the long–term goals of urban sustainability. As such, it requires that 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.

3.2 Urban sustainability

The concept "sustainability" has been applied to urban planning since the early 1990s. There is no canonical definition of urban sustainability in the literature as this concept is too complex and sweeping to be delineated as a concept. This is due to its contested, multifaceted, and normative nature. Generally, urban sustainability refers to a state of change in which the city doesn't undermine the natural and social systems, which could occur through resource intensive consumption and depletion, pollution, environmental degradation, and hazardous substances, as well as through social instability/insecurity, social inequality, public health decrease, and social hazard. These can make people subject to conditions that inhibit their ability to satisfy their needs and pursue their aspirations. To put it differently, urban sustainability means a desired state in which the city strives to achieve a balance between environmental protection and integration, economic development and regeneration, social equity and stability, and resilient physical structure and its efficient operation as long–term goals through the strategic process of sustainable development as a desired trajectory. While urban sustainability has evolved as a proposal to overcome the environmental and socio–economic problems and challenges associated with the rapid urbanization of the world, there are a number of interdisciplinary frameworks that have attempted to conceptualize it in various, and sometimes distinct, ways and hence to offer different access roads to the topic of urban sustainability. Regardless, the ultimate goal of urban sustainability is to develop human settlements and environments that are healthy, livable, and equitable together with minimal demand on natural resources and thus minimal impacts on the environment. Furthermore, urban sustainability is often cast in terms of four dimensions: environmental, economic, social, and physical which should together—as interdependent and synergic pillars—be enhanced over the long run in line with the goals of sustainability. It articulates how the city values the environment, the equity, the economy, and the built form.

3.3 Sustainable urban development

The concept "sustainable development" has been applied to urban development since the early 1990s, a few years after the widespread diffusion of the concept of sustainable development in 1987. This resulted from the then realization that the predominant paradigm of urban development was oblivious to the risks of, and triggering, environmental upheavals and crises, as well as of the effects of, and worsening, social vulnerability and injustice, causing environmental and social deprivation within cities. Achieving the goals of urban sustainability requires finding and fostering linkages between scientific and social research, technological developments and innovations, institutional structures and practices, regulatory policy design and planning, and governance and citizen participation. This can occur through developing and bolstering strategies and solutions that facilitate the design, development, implementation, evaluation, and improvement of urban systems and other practical interventions within various urban domains that promote sustainability in terms of replenishing resources, lowering energy use, lessening pollution and waste levels, and improving social justice, stability, and safety. The strategies and solutions developed with these underlying objectives epitomize what sustainable development is. Accordingly, sustainable urban development refers to a process of change in the built environment that seek to foster economic development and enhance the quality of life while wisely managing and conserving natural resources while promoting the health of citizens, communities, and ecosystems. In the context of this paper where the focus is on data-driven smart sustainable cities, achieving the goals of urban sustainability through sustainable urban development occurs with support of the IoT and big data technologies and their novel applications, data-driven smart solutions for urban management in terms of development planning and operational functioning management. The way forward is to integrate the research and innovation agenda of advanced ICT with the agenda of sustainable development while aligning and mobilizing urban actors around common strategic goals, thereby justifying emerging and future ICT investment and its orientation by addressing physical infrastructure inefficiencies, environmental concerns, and socio–economic needs. To sustain this momentum requires innovative policy frameworks, effective institutional structures and practices, and concrete planning measures.

However, achieving urban sustainability is of an enormous challenge due to the conflicts that exist between the fundamental goals of sustainable urban development. These conflicts in turn are challenging to deal with and daunting to overcome as many experiences from real-world cities have shown since the widespread diffusion of sustainable development in the late 1980s. That is to say, tackling these conflicts has been, and continues to be, one of the toughest challenges facing urban planners and scholars as to decision–making and action–taking in the context of sustainable cities, smart cities, and smart sustainable cities. Despite the appealing and holistic character of sustainable urban development approach into evading or mitigating those conflicts, they "cannot be shaken off so easily" as they "go to the historic core of planning and are a leitmotif in the contemporary battles in our cities," rather than being "merely conceptual, among the abstract notions of ecological, economic, and political logic" (Campbell, 1996, p. 296). Yet, sustainable development as a long–range objective for achieving the goals of sustainability constitutes a worthy strategic approach for planners, scholars, and policymakers to reach the required level of sustainability with support of advanced technologies and their novel applications. Campbell (1996, p. 9) contends that urban planners and developers, in particular, will in the upcoming years "confront deep–seated conflicts among economic, social, [physical] and environmental interests that cannot be wished away through admittedly appealing images of a community in harmony with nature. Nevertheless, one can diffuse the conflict, and find ways to avert its more destructive fall–out." To put is differently, sustainable urban development advocates can—and ought to—seek ways to make the most of all of its value–sets at once. This is in contrast to keeping on playing them off against one another. In this light, the synergistic and substantive effects of sustainability on urban planning and development require cooperative effort, collaborative work, and concerted action from diverse urban stakeholders in order to take a holistic perspective on the complex challenges and pressing issues facing contemporary cities.

3.4 Sustainable urbanism

Urbanism is concerned with the study of urban phenomena in terms of the urbanization and organization of cities, as well as the practice of urban planning and development. Rooted in the study of the relationship of urban planning and development and sustainability and sustainable development, sustainable urbanism is concerned with the study of cities and the practices and strategies to design and develop them that focus on promoting their long-term resilience and viability through reducing material use, lowering energy consumption, mitigating pollution, and minimizing waste, as well as improving social equity and human well-being.

There are different notable works that have furthered the knowledge base and diffusion of sustainable urbanism. One of which is the book "Sustainable Urbanism" by Doug Farr in 2008. According to the author, this approach to urbanism aims to eliminate the environmental impacts of urban development by supplying and providing all resources locally, and to evaluate the full life cycle of ecosystem and public services and goods from production to consumption with the purpose of eliminating environmental externalities (Farr, 2008). Accordingly, it emphasizes both environmental and physical factors by designing communities that are walkable and transit–served so that people can meet their daily needs by walking. Farr's definition of sustainable urbanism is based on bringing everything closer together, being more efficient, using higher quality goods, having everything within walking distance, and closing the loop (Sharifi, 2016). The key emphasis here is on sustainable transportation, which is a key design strategy underlying the compact city.

Subsequently, a significant body of research and practice has broadened the approach of sustainable urbanism considerably to include social, economic, welfare, and public health factors, among others, thereby taking it beyond an urban design field into all of urban planning, policy, and development areas (Haas, 2012). The United Nations has incorporated sustainable urbanism into its global sustainable development goals, specifically SDG 11: Sustainable Cities and Communities (United Nations, 2015c). Consequently, a wide range of institutions, organizations, and governments are promoting and researching sustainable urbanism practices and strategies. The key defining elements of sustainable urbanism, which have been enacted in many cities across the world, include and combine a diversity of concepts and themes pertaining to compact cities and eco–cities (see, e.g., Beatley, 2010; Bibri, 2020a; Farr, 2008; Williams et al., 2000; Kenworthy, 2006; Lynn, Geoffrey, & Santore, 2003; Neuman, 2011; OECD, 2012a, b).

Not much has been said regarding the criticism of sustainable urbanism. There are some views that are concerned with the use of sustainable urbanism as a branding hoax that risks debasing the term 'sustainable' with some developments labeled as examples of "sustainable urbanism." Such developments, albeit substantially much better than modern developments, are not considered truly sustainable according to the criteria of sustainable development.

3.5 Compact urbanism

Compact urbanism is concerned with the study of the form of cities and the practices and strategies to plan and design them that focus on securing environmentally sound, economically viable, and socially beneficial development through dense and mixed land use development patterns that rely on sustainable transportation and favor green space and parks. As such, compact urbanism plays a significant role in responding to the needs of urban areas. It lessens the impact on the environment, with shorter intra-urban distances and reduced automobile use. It contributes to the economy by increasing the efficiency of infrastructure investment and by giving residents easier access to services, faculties, jobs, and social networking. A key indicator used to measure compact city policy outcomes is "compactness" (density, mixed land use, diversity, public transport, and access by proximity). It is important to, as part of compact urbanism practices, strategies, policies, to set explicit goals, encourage dense and contiguous development at urban fringes, retrofit and transform existing built-up areas, enhance diversity and quality of life in urban centers, minimize adverse negative effects (see, e.g., Bibri et al., 2020; Hofstad, 2012; OECD, 2012a, b for illustrative/descriptive case studies).

Compact urbanism defines the core of sustainable urbanism, and the compact city is the paradigm of sustainable urbanism. This city model has, over the last 40 years, been the preferred response to the challenges of sustainable development. Compact urbanism is strongly promoted by global and local policies due to its positive outcomes in terms of contributing to the economic, environmental, and social goals of sustainability. The key policy issues related to compact urbanism include: how compact cities contribute to urban sustainability, how compact city policy outcomes can be evaluated, how policy responses can be tailored to different local circumstances, and what governance challenges exist in developing and implementing compact city policies in different metropolises (OECD, 2012a, b). Compact urbanism involves several 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. Research within compact urbanism involves a variety of perspectives, including urban theory, planning theory, planning practice, design practice, policy, resilience, sustainability, morphology, complexity theory, systems thinking, action net theory, actor network theory, spatial analysis, regenerative design, economics, in addition to comparative and discursive studies. Bibri (2020c) provides a comprehensive state–of–the–art review of compact urbanism as a set of planning and development practices and strategies, focusing on the three dimensions of sustainability and the significant, yet untapped, potential of big data technology for enhancing such practices and strategies under what is labelled "data–driven smart sustainable urbanism." The author also provides a critical discussion of compact urbanism from the perspective of Science, Technology, and Society (STS) in terms of linkages and concerns.

3.6 Ecological urbanism

Over the past two decades, ecological urbanism has gained significant traction and its scope has broadened to cover multiple dimensions of sustainability. Ecological urbanism and green urbanism are common terms that are related to sustainable urbanism. It is argued that ecological urbanism draws from ecology to inspire an urbanism that is more sensitive to the environment and also socially inclusive. This is predicated on the assumption that ecology is concerned with the relationships between all organisms and the environment. Ecological urbanism is also less ideologically driven, i.e., by ideas of a political or economic nature, than green urbanism whose principles are based on the triple–zero framework: zero fossil–fuel use, zero waste, and zero emissions. However, both approaches to urbanism are construed as focusing more on the natural environment and ecosystems and less on economic and social aspects (Mostafavi & Doherty, 2010).

Ecological urbanism shares several concepts, ideas, and visions with green urbanism in terms of the role of the city and positive planning and development in shaping better places, communities, and lifestyles.

Ruano (1998) defines ecological urbanism as the development of multi–dimensional sustainable human communities within harmonious and balanced built environments. Ecological urbanism focuses on developing urban environments based on the principles of ecological sustainability. If ecological urbanism as a holistic approach is to be successful, it needs to design and integrate complex systems and social processes together, and to reflect their synergy in ways that are dynamically interactive or cooperative to produce combined effects greater than the sum of their separate effects with respect to the benefits of sustainability as to its tripartite composition. It is of crucial importance for cities to become masters of a stable, equitable, and ecological urbanism (Brugmann, 2009). In many ways, ecological urbanism is an evolution, and a critique of, landscape urbanism, arguing for a more holistic approach to the planning, design, and management of cities. However, the lack of a true merger of landscape architecture with urban ecology has led Steiner (2011) to introduce landscape ecological urbanism as an approach that can include urban ecology. Kuitert (2013) demonstrates how such integrative urban planning and management should rely on analysis.

With the model of smart urbanism gaining momentum, it has become feasible to achieve important environmental improvements by integrating it with that of ecological urbanism. Both of these models are becoming highly responsive to data-driven solutions to improve and advance environmental sustainability under what can be labelled "data-driven smart ecological urbanism." This is illustrated in Fig. 1 based on the outcomes of the case study done on environmentally data-driven smart sustainable cities (Bibri & Krogstie, 2020c). Through investments in smart eco-city initiatives, planners, ICT experts, and policymakers intend to promote and develop innovative solutions to confront the significant challenges posed by the escalating trend of urbanization and the alarming rate of climate change. However, the integration of ecological urbanism and smart urbanism (e.g., Shahrokni et al., 2014a, b; Shahrokni, Levihn and Brandt, 2014; Shahrokni et al., 2015a, b; Shahrokni, Lazarevic, & Brandt, 2015) is justified by the problematic nature of eco-cities as to their contribution to the goals of sustainability when it comes to planning and design. This pertains mostly to the question of how eco-cities should be monitored, understood, analyzed, and planned so as to optimize, enhance, and maintain their performance over the long run. Therefore, data-driven technologies have become essential to the functioning of eco-cities. In this regard, they are offering many new opportunities for enhancing decision-making concerning the practice of controlling, managing, regulating, and governing eco-cities. Bibri (2020b) provides a comprehensive state–of–the–art review of the field of ecological urbanism in terms of foundations, models, strategies, research issues, as well as data–driven smart technological trends. Bibri (2020a) provides a detailed critical discussion of ecological urbanism from a variety of perspectives.

3.7 Smart urbanism

In contrast to the smart city as a policy concept, smart urbanism is an emerging academic field, which analyzes and reflects on the varieties and outcomes of smart city development. This involves a large body of mainly applied studies that highlight the opportunities, potentials, and benefits of the solutions of the smart city in its various faces. Smart urbanism examines how smart city policies operate in contemporary cities. Central to smart city policies are emerging digital technologies, big data, and computational processes to monitor, understand, control, manage, regulate, and plan urban infrastructures, resources, risks, and citizens. This materializes as sensor

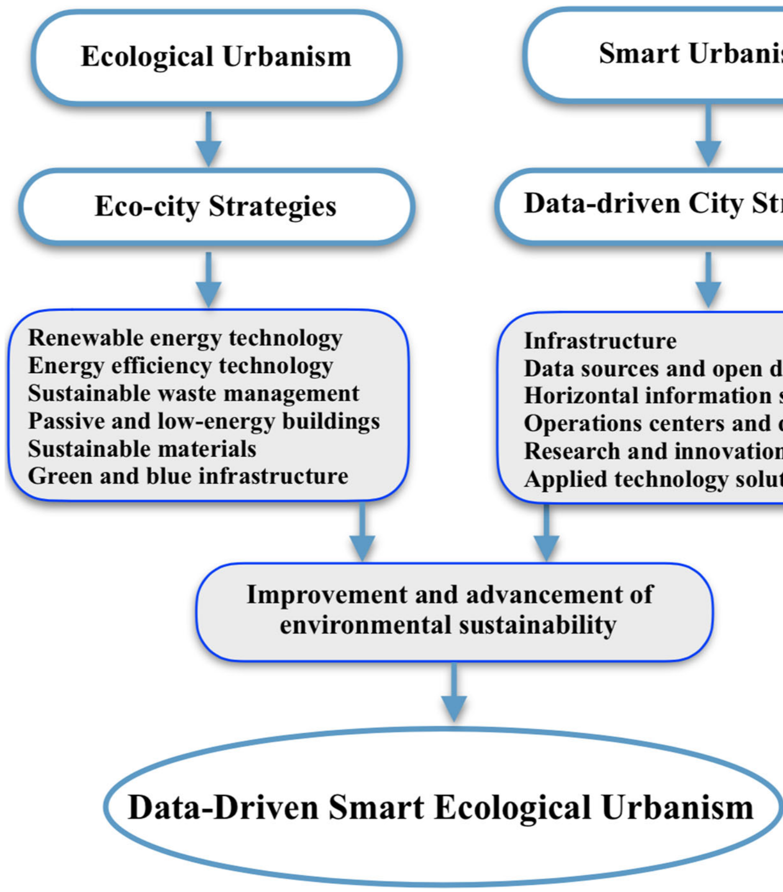

Fig. 1 A framework for data-driven smart ecological urbanism

networks, horizontal information systems, urban dashboards, urban operations centers (e.g., control rooms and situation centers), and other institutional practices and competences (Bibri & Krogstie, 2020b, c; Kitchin, 2014, 2015, 2016; Marvin et al., 2016; Nikitin et al., 2016). However, due to the infancy of the field, its disciplinary fragmentation, the work on smart urbanism lacks "theoretical insight and empirical evidence required to assess the implications of this potentially transformative phenomenon" (Luque-Ayala & Marvin, 2015, p. 2106).

Smart urbanism is widely promoted by national and local governments, international organizations, and businesses and industries alike. It provides a flexible and responsive means of addressing the challenges of urban growth and renewal, tackling environmental problems, and building a more socially inclusive society. This emerging academic discourse, a language of smartness, is reshaping debates about contemporary cities, along with a new set of programs and practices that are aimed at realizing smart urbanism (see, e.g., Bibri & Krogstie, 2020b; Eden Institute Strategy, 2018; Mora & Bolici, 2016; Noori et al., 2020; Nikitin et al., 2016). This is visible in the importance given to the smart city approach in diverse plans and initiatives in Europe, the UK, the USA, Asia, Australia, and elsewhere, and in the emergence of dedicated teams aimed at developing business opportunities in smart urban development projects, such as IBM, Cisco, Google, General Electric, and others. Smart urbanism is projected, often following normative approaches, as a futuristic solution brought to the present to deal with a broad multiplicity of urban maladies, including issues of unsustainable transport, traffic congestion, resource scarcity, climate change, and even the need to expand democratic access, juts to name a few. In this context, smart urbanism is increasingly embracing a number of strategies from sustainable urbanism as drivers for fostering emergence and materialization, including:

- Compactness in terms of proximity, contiguity, and concentration
- Complexity in terms of rich, varied, cumulative benefits of mixed land use development
- Connectedness in terms of sustainable transport modes as a consequence of coherent networks and proximity

- Cohesiveness in terms of sense of community, belongingness, and multi-stakeholder collaboration
- Liveability in terms of education and recreational possibilities
- Ecological solutions such as green energy, integrated renewable solutions, and sustainable waste management.

Concurrently, smart urbanism is contributing to improving and advancing sustainability in a variety of ways in the ambit of sustainable urbanism. It is deeply rooted in normative visions of the future where new technologies and their novel applications stand as the primary driver for change. Moreover, it originates in the belief that place uniqueness is reflected against the backdrop of a clearly defined urban order, usually of a spontaneous and unpredictable character. This provides the necessary framework for urban diversity and the palette for the city of a plethora of design ideas.

However, the significant risks of smart urbanism calls for critically engaging with its far-reaching societal implications. The literature on smart urbanism appears most frequently focused on the realization of technological solutions (Letaifa 2015), such as big data computing, cloud computing, the IoT, artificial intelligence, 5G, and industry 4.0, rather than providing a critical understanding of its conceptual undermining and negative implications. There is a lack of the theoretical basis and empirical evidence required to holistically evaluate the potential effects and hidden agenda of the transformative processes within smart urbanism in connection with the practices, operations, and institutions of modern society (Bibri 2021). A number of studies have been carried out in more recent years that address the ramifications of smart urbanism and the related driving socially disruptive technologies, drawing on several theories and theoretical perspectives.

While smart urbanism as underpinned by big data offers seemingly seductive visions of the future, it also raises a number of concerns. The idea of big data being only as good as the modelling underlying its use exacerbates technocratic reductionism (Söderström, Paasche and Klauser 2014). Technocratic governance is inherent in smart urbanism, and there is also a lack of attention on what actually lies beyond the demarcations associated with what happens within city administrative boundaries. Kitchin (2014) provides a critical reflection on the implications of big data and smart urbanism, examining technocratic governance and city development; corporatization of city governance and technological lock-ins; the politics of big urban data; buggy, brittle and hack-able cities; and the panoptic city. Kitchin (2015) critically examines a number of urban data issues, including, in addition to corporatization and anticipatory governance, ownership, control, privacy and security, and technical challenges in the context of data-driven, networked urbanism and smart cities. Examining the forms, practices, and ethics of smart cities and urban science, Kitchin (2016) gives particular attention to privacy, dataveillance and geo-surveillance, and such data uses as social sorting and anticipatory governance. In a nutshell, smart urbanism ignores social, political, cultural, economic, and historical contexts shaping urban life, thereby curtailing the opportunities for wider perspectives.

The majority of the critique of smart urbanism discusses its potential risks on urban society, or on how it has transformed the urban way of life, including social interactions, urban space, power relationships, and urban regulations. Smart urbanism as an emerging scholarly field still lacks empirical evidence and theoretical embedding of these concerns. The outcome of supply oriented, technocratic governance of smart cities (e.g., Kitchin, Lauriault and McArdle 2015; Marvin, Luque-Ayala and McFarlane 2015) seems to be highly unequal urban societies, characterized by unequal power relations, large gaps between those with access to information services or opportunities and those without, social exclusion, and unequal distributions of costs and benefits (Datta 2015; Kitchin et al. 2016; Luque-Ayala, McFarlane and Marvin 2014). This is due to putting much emphasis on the role of technology in collecting and analyzing data to extract knowledge in the form of applied intelligence to enhance government operations and automate urban system functions (Jiang et al. 2020; Verrest and Pfeffer 2019; Kitchin et al. 2014, 2016). However, while smart urbanism offers great potential to enhance the quality of life, it also leads to the marginalization of certain groups and create multiple divides between those who have access to smart applications and those who do not in relation to public transport, mobility, healthcare, education, utilities, and so on. Social exclusion issues in smart urbanism go beyond access to technology to include the distortion of the "reality of a city" and the particularities of localities, such as the history, feelings, concerns, knowledge, and trajectories of the existing urban communities (McFarlane and Söderström 2017). In other words, while smart urbanism seems to highlight the importance of the quality of life at the discursive level, it tends to distort the individuality of the existing neighborhoods and strip off the particularities of the existing urban fabrics.

3.8 Data-driven smart sustainable urbanism

As an emerging academic field, **s**ustainable urbanism examines the policies, practices, and strategies to plan, design, and develop cities that promote and contribute to sustainable development based on advanced ICT in terms of reducing material use, lowering energy consumption, reducing pollution, and minimizing waste, as well as improving social justice, social inclusion, social cohesion, social capital, and the quality of life. The underlying technical dimension involves the use and application of computational and scientific approaches and processes for city development planning and operational management. Recent evidence lends itself to the argument that an integration of the defining elements of sustainable urbanism (physical structures, urban forms, spatial organizations, natural resources, urban infrastructures, socio–economic networks, and ecosystem and human services, etc.) with data-driven technologies can create more sustainable, efficient, resilient, livable, safe, and equitable cities.

Data-driven smart sustainable urbanism is an emerging approach to sustainable urban development, a strategic process to achieve the long–term goals of urban sustainability—with support of advanced technologies and their novel applications, especially the IoT and big data analytics. Achieving the status of smart sustainable cities epitomizes an instance of urban sustainability. This notion refers to a desired state in which a city strives to retain a balance of the socio–ecological systems through adopting strategic sustainable development as a desired trajectory. This balance entails improving and advancing the environmental, economic, social, and physical systems of the city in line with the vision of sustainability over the long run—given their interdependence, synergy, and equal importance. This long-term goal requires fostering linkages between scientific research, technological innovations, institutional frameworks, policy formulations, planning practices, and development strategies in relevance to sustainability.

Smart sustainable urbanism rely on constellations of instruments across many scales that are connected through multiple networks characterized by intelligence and high penetration and speed, which provide continuous data regarding the different aspects of urbanity in terms of the flow of decisions about the environmental, economic, social, and physical forms of the city. Digital instrumentation involves the infrastructure and devices that produce urban big data using the collective tools, processes, methods, techniques, and technologies that also transform the city into a data-driven enterprise (datafication). The generated data in turn enable real-time analysis of city life (computation). Digital instrumentation opens up dramatically different forms of urban management. Its essence revolves around the need to coordinate and integrate technologies that have clear synergies in their operation and need to be coupled so that many new opportunities can be realized.

The evolving practice in the field of smart sustainable urbanism tends to focus on harnessing and exploiting the ever–increasing deluge of data that flood from urban systems and domains by leveraging the value extracted through analytics in enhancing decision making and generating deep insights pertaining to a wide variety of sustainability uses and applications. The emerging data–driven smart solutions have become of paramount importance to smart sustainable urbanism as a set of processes and practices. One key aspect of this is the use of urban data as the evidence base for formulating urban policies, plans, strategies, and programs themselves, as well as for tracking their effectiveness and modelling and simulating future urban development projects. In addition, the operation and organization of urban systems and the coordination of urban domains require not only the use of complex interdisciplinary knowledge, but also the application of sophisticated approaches and powerful engineering solutions underpinned by advanced computational analytics. Modern cities employ the latest technologies in city management to support sustainable development given rapid urban growth, increasing urban domains, and more complex infrastructure.

There still is a little understanding about how and why data–driven smart sustainable urbanism has emerged and materialized and is functioning and evolving. In this respect, Bibri (2019d) has recently conducted a study in STS, examining the intertwined societal factors driving its materialization, success, expansion, and evolution, and further critically discusses 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, and also shape, socio–cultural and politico–institutional structures. And it 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 production and policy–making. However, as argued by the author, there is a need for re–casting urban science and big data analytics 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. In an earlier study in STS, Bibri and Krogstie (2016) analyze the nature, practice, and impact of ICT of ubiquitous computing for sustainability in the defining context of smart sustainable cities. Specifically they probe the ways in which this form of science and technology (S&T) has emerged from different perspectives, why it has become institutionalized and interwoven with politics and policy—urban dissemination, as well as the risks it poses to environmental sustainability in the context thereof. Their study reveals that smart sustainable cities are medicated by and situated within the ecologically and technologically advanced societies, and as urban manifestations of scientific knowledge and technological innovation, they are shaped by, and also shape, socio–cultural and politico–institutional structures, to reiterate. However, this form of S&T is shown to pose risks to environmental sustainability. Therefore, it needs to be reoriented in a more sustainable direction, as it cannot, as currently practiced, solve the complex environmental problems placed in the agenda of smart sustainable cities as a holistic approach to urbanism.

3.9 Urban informatics

Urban informatics did not emerge as a notable field of research and practice until around the mid 2000s. Subsequently, a number of books have been published on the topic (e.g., Foth, 2009; Foth, Choi, & Satchell, 2011; Ratti & Claudel, 2016; Shepard, 2011; Townsend, 2013; Unsworth, Forte, & Dilworth, 2014), which further demonstrate the increasing notability and significance of the field of urban informatics. This field is concerned with the study of humans in their interaction with computer and information systems, or people creating, applying, and using ICT and data, in the context of urban environments or areas. The emerging area of urban informatics focuses on the exploration and understanding of urban systems by leveraging novel sources of data.

There are different definitions of urban informatics as an interdisciplinary field of research and practice. According to Foth et al. (2011), urban informatics refers to "the study, design, and practice of urban experiences across different urban contexts that are created by new opportunities of real–time, ubiquitous technology, and the augmentation that mediates the physical and digital layers of people networks and urban infrastructures." Kitchin (2016) describes it as a human–computer interaction and informational approach to examining and communicating urban processes. Furthermore, this field draws on three broad domains: people, place, and technology (Foth et al., 2011). People from different socio–cultural backgrounds include residents, citizens, and community groups, in addition to the social dimensions of organizations and institutions. Place includes both urban sites, locales, and habitats, as well as regions, districts, neighborhoods, public spaces, and other kinds of urban areas. Technology involves various forms of urban computing.

Urban computing denotes collecting, integrating, processing, analyzing, and synthesizing heterogeneous data (Zheng et al., 2014) for some purpose, ways of improving sustainability, efficiency, resilience, equity, and the quality of life. In the context of data-driven smart sustainable urbanism, urban computing entails using a set of devices, systems, platforms, infrastructures, networks, and related algorithms, techniques, processes, and protocols for the purpose of addressing and overcoming the issues engendered by urban growth through analyzing, harnessing, and leveraging various kinds of urban data (e.g., transport data, human mobility data, traffic flow data, spatiotemporal data, environmental data, energy data, socio–economic data, government data, and user data) in ways that extract useful knowledge to enhance decision–making processes pertaining to urban operational functioning, management, planning, and governance with respect to sustainability.

Urban computing as an interdisciplinary field involves a range of scientific and technological areas, including computer science, information science, data science, information technology, information systems, computer engineering, software engineering, and wireless networks, as well as city-related or urban planning fields, including sustainable development, strategic thinking, environmental planning, transportation planning, land–use planning, landscape architecture, and urban design, all converging in the context of urban environments or spaces. As an academic and research field, urban computing deals with the study, design, development, and implementation of computing technology in urban domains. Specifically, it is concerned with:

- designing and constructing urban–oriented systems and applications and making them behave intelligently as to decision support and service delivery to achieve multiple urban goals;
- representing, modeling, processing, and managing various kinds of urban data;
- collecting information and discovering knowledge for various purposes; and
- designing and applying evaluation methods for improving and maintaining the operation of computer systems and applications

Urban computing employs many of the technological paradigms introduced by ubiquitous computing, which represents an era when, in the urban context, computer technology in all its forms disappears into urban environments and recedes into the background of urban life. Such paradigms (e.g., the IoT, Ambient Intelligence, Sentient Computing) share the same core enabling technologies, namely sensing devices, data processing platforms, computing infrastructures, and wireless communication networks. These are to function unobtrusively and invisibly in the background of urban life and to help optimize urban operational functioning, improve urban management and planning, enhance the quality of life of citizens, understand the nature of urban phenomena, and predict urban changes and dynamics. Important to add, Foth (2009) differentiates urban computing from urban informatics by suggesting that the former focusses more on technology and computing, and the latter focusses more on the social and human implications of technology in cities, i.e., the relationship between technology and urbanity, as expressed through the many dimensions of urban life.

The field of urban informatics draws on social, scientific, technological, spatial, and urban research domains, including, combined, urban sociology, cultural studies, communication studies, urban planning, urban design, spatial planning, urban studies, geography, urban engineering, transportation engineering, landscape architecture, environmental engineering, geo–informatics, computer science, data science, software engineering, and human–computer interaction. The research domains of urban informatics are reflective of the diversity of the methodologies being used in its pursuit and practice. The field of urban informatics borrows from a wide range of methodologies across the social sciences, humanities, arts, design, architecture, planning, ICT, and computing, and applies them to the domain of urbanism. Examples of such methodologies include action research, participatory action research, critical theory, social theory (e.g., Batty, 2013; Foth & Brynskov, 2016; Hearn, Tacchi, Foth, & Lennie, 2009; Satchell, 2008), grounded theory, spatial analysis, participatory design, and interaction design. In addition, there is a longer legacy of scientific and informatics approaches to cities that provide a bedrock of knowledge, which originates in digital mapping and geographic information systems, quantitative geography and urban modeling, and urban cybernetics theory and practice (Kitchin, 2016).

Since urban informatics became a notable field of research and practice in the mid 2000s, the prevalence of ICT, the growing popularity of ubiquitous computing, the access to open data, the use of big data analytics, as well as the spread of smart cities have contributed to a surge in interest in this field. This is manifested in various actors seeking to explore and exploit the new possibilities and opportunities of urban informatics. Specifically, there are numerous actors involved in the academic and practical aspects of the field, including scholars, technical planners, industry experts, engineers and architects, computer and data scientists, and urban scientists, all undertaking research and developing technologies to tackle the challenging elements of urbanism using new approaches increasingly enabled and fueled by the emerging paradigm of big data computing. This adds to the work of city governments in terms of formulating and implementing regulatory policies and devising and applying political mechanisms to promote and spur innovation within urban informatics. In terms of research and applications, according to Thakuriah, Tilahun, and Zellner (2017), the major potential of urban informatics lies in four areas: (1) improved strategies for dynamic urban resource management, (2) theoretical insights and knowledge discovery of urban patterns and processes, (3) strategies for urban engagement and civic participation, and (4) innovations in urban management, and planning and policy analysis. Overall, as pointed out by Foth et al. (2011) and Townsend (2013), urban informatics emphasizes the new opportunities (including real–time data) for both citizens and city administrations enabled and afforded by ubiquitous computing, in addition to the convergence of physical and digital aspects of the city.

4 Established and emerging scientific disciplines or fields

A scientific discipline refers to a particular branch of scientific knowledge as based on the scientific approach—hypothesize, model, and test. This approach denotes a set of principles and procedures employed for the systematic pursuit of knowledge involving the formulation of hypotheses, the collection of data through observation and experiment, and the testing of hypotheses. This paper is concerned with different branches of science, including applied sciences, which apply existing scientific knowledge to develop more practical applications, such as data-driven solutions; formal sciences, including mathematics and logic as related to big data computing; and social sciences as part of urban informatics and urban planning and development. The set of academic disciplines introduced and described below are identified on the basis of their relevance to the interdisciplinary and transdisciplinary field of data-driven smart sustainable urbanism where the underlying theories are a foundation for practice.

4.1 Computer science

Often described as one of the parents of data science, computer science is concerned with the study of the theoretical foundations of information (e.g., structures, representation, etc.) and computation (e.g., mechanisms, algorithms, etc.) and the practical techniques and methods for their implementation in computer systems. In other words, it is the scientific and practical approach to computation and its applications and the systematic study of the feasibility, structure, expression, and mechanization of the methodical procedures that underlie the acquisition, representation, storage, processing, analysis, communication of, and access to information. In short, it is the study of the theory, experimentation, and engineering that form the basis for the design and use of computer systems. As a discipline, computer science spans a range of topics from theoretical studies of algorithms and the limits of computation to the practical issues of implementing computing systems in hardware and software.

Computer scientists deal with the systematic study and development of algorithmic processes that describe, create, and transform information and formulate abstractions (or conceptualizations) to model, simulate, and design complex systems. They therefore specialize in the theory of computation and the design of computational systems. A number of computer scientists argue for the distinction of three separate paradigms in computer science. Wegner (1976) contends that those paradigms are science, technology, and mathematics. Denning et al. (1989) contend that they are theory, abstraction (modeling), and design. Eden (2007) describe them as the "rationalist paradigm" (which treats computer science as a branch of mathematics as prevalent in theoretical computer science and mainly employs deductive reasoning), the "technocratic paradigm" (which is found most prominently in software engineering), and the "scientific paradigm" (which approaches computer–related artifacts from the empirical perspective of natural sciences, identifiable in some branches of artificial intelligence).

The fields of computer science can be divided into a variety of theoretical and practical disciplines, including computational complexity theory, programming language theory, computer programming, human–computer interaction, and artificial intelligence. In more detail, there are several areas that are crucial to the discipline of computer science, including theory of computation, algorithms and data structures, programming methodology and languages, and computer elements and architecture, in addition to software engineering, artificial intelligence, computer networking and communication, database systems, parallel computation, distributed computation, human–computer interaction, computer graphics, operating systems, and numerical and symbolic computation. Among the areas of computer science that underpin the practice of data-driven smart sustainable urbanism in terms of computational systems include, but are not limited to:

4.1.1 Data structures and algorithms

The study of commonly used computational methods and their computational efficiency. These structures and algorithms are of relevance to the functioning of big data applications in the context of smart sustainable cities. Big data analytics should involve highly sophisticated and dedicated techniques and algorithms associated with machine learning, data mining, statistics, database query, and so on that can perform complex computational processing of data for timely and accurate decision–making purposes. New approaches to storing, managing, coordinating, and analyzing big data and processing context information should rely on advanced artificial intelligence programs.

4.1.2 Theory of computation

This area deals with the fundamental question underlying computer science. That is, what can be (efficiently) automated (Denning, 2000). Theory of computation is focused on answering questions about what can be computed and what amount of resources are required to perform those computations. This is of particular relevance to many urban problems in the sense of using computability theory to examine which are computationally solvable on various theoretical models of computation (see Bettencourt, 2014 for illustrative examples of computationally intractable problems in relation to smart urbanism). In relation to smart sustainable cities, ICT is focussed on defining critical problems that emerge rapidly and unexpectedly, some of which reveal critical infrastructures. The analysis of such problems and their identification is crucial to the sustainability of smart sustainable cities. These are far–from–equilibrium, dominated by fast and slow dynamics in short and long cycles. Regardless, many routine functions in cities are being replaced by computer control and various forms of automation are increasingly being blended with human actions.

4.1.3 Concurrent, parallel, and distributed systems

In such systems several computations execute simultaneously and potentially interact with each other. A distributed system extends the idea of concurrency onto multiple computers connected through a network. Computers within the same distributed system have their own private memory, and information is often exchanged among themselves to achieve a common goal. This relates to cloud computing and fog computing as models for performing big data analytics in relation to diverse applications in the context of smart sustainable cities. Part of the process of coordination and integration using state–of–the–art data systems and distributed computing must involve ways in which the citizenry is able to participate and to blend their personal knowledge with that of experts who are developing the same technologies (Batty et al., 2012).

4.1.4 Computer network

Computer network aims to manage networks between computers across different geographical areas. This is of high relevance to urban domains in the context of smart sustainable cities. To develop technologies that ensure widespread participation, for example, new ICT is essentially network–based and enables extensive interactions across many domains and scales (Batty et al., 2012).

Wireless network technologies include satellite–enabled GPS, mobile phones, LPWAN, and Wi–Fi networks for collecting and coordinating data in terms of the data themselves and how that data are stored and made accessible. ICT of pervasive computing will result in a blend of smart applications enabled by constellations of instruments across many spatial scales linked via multiple networks for providing continuous data flowing from various urban domains (processes, activities, movements, interactions, observations, etc.), This can provide a fertile environment conducive to advancing the contribution of smart sustainable cities to sustainability over the long run by monitoring, understanding, analyzing, and planning them in ways that strategically assess, improve, and sustain this contribution.

4.1.5 Computer security

Computer security aims to protect information from unauthorized access, disruption, or modification while maintaining the accessibility and usability of the system for its intended users. Security is highly important to ensure that all technological components associated with big data applications for smart sustainable cities are supported by security measures. Massive repositories of urban data are at stake, and failure to protect these data will pose risks and threats to the functioning of such applications, as well as to the safety and well–being of citizens. Therefore, security measures should be at the center of urban policy and governance practice associated with the design, development, deployment, and implementation of applied data-driven technology solutions within smart sustainable cities. Any attempt of an unauthorized access, malicious attack, or abuse of information on citizens, infrastructures, networks, and facilities can compromise the integrity of these solutions and related applications and services. Smart sustainable cities generate colossal amounts of data on virtually every urban process, which must be securely maintained for processing, analysis, and sharing. Urban environments are now being continually forged in sensorial, informational, and communicative processes. It is a world where smart sustainable cities think of us, where the environment reflexively monitors our behavior, including the extent to which we behave in a sustainable way through the activities and processes we perform on a daily basis.

4.1.6 Human–computer interaction (HCI)

A common thread running through most definitions of HCI is that it deals with the study, development, and implementation of the interaction between users and computers. HCI can be defined as a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them. HCI is the process of communicating information from or presenting services by computer systems via display units to human users as a result of the manipulation and control of these systems by means of explicit or implicit input devices. Its special concerns include: the joint performance of tasks by users and computers; the structure of communication between users and computers; human capabilities to use computers; algorithms and programming of user interfaces; engineering issues relating to designing and building interfaces, the process of analysis, design and implementation of interfaces; and design trade–offs. HCI also deals with enhancing usability and learnability of interfaces; techniques for evaluating the performance of interfaces; developing new interfaces and interaction techniques; developing and applying design methodologies to real–world problems; prototyping new software and hardware systems; exploring new paradigms for interaction (e.g., natural interaction); and developing models and theories. As to developing new technologies for communication and dissemination, new sources of urban data, the articulation of urban problems, plans and policies, and all the apparatus used in engaging the community in developing smart sustainable cities require new forms of online participation making use of the latest ICT in terms of state–of–the–art HCI and distributed computation (Batty et al., 2012).

4.1.7 Artificial intelligence

Artificial Intelligence (AI) is a technology that mimics human intelligence. This subfield of computer science is concerned with understanding the nature of human intelligence and creating machines capable of emulating the natural intelligence displayed by humans. McCarthy (2007) defines AI as “the science and engineering of making intelligent machines.” Accordingly, AI involves the modeling and simulation of human cognitive and behavioral aspects into machines, such as reasoning, inference, learning, language production, problem-solving, decision–making, and action-taking. Implementing aspects of human intelligence in computer systems is one of the main practical goals of AI within data-driven smart sustainable cities of the future. One of the key uses of AI techniques in this context is to identify, understand, model, and simulate situations of urban life and implement them in computer systems so that they become able to adaptively, proactively, or knowledgeably take the most relevant actions, e.g., based on context-aware computing or big data computing in terms of decision-making. Both of these advanced technologies involve highly sophisticated and dedicated techniques and algorithms associated with data mining, machine learning, statistical analysis, predicting modelling, and database query. These can perform complex computational processing of data for timely and accurate decision–making purposes. Big data can be better managed through AI processes, which render systems faster and more intelligent. More recently, AI applications have become an integral part of many urban domains. Urban AI manages transport systems, energy systems, traffic systems, communication systems, distribution networks, and even health systems, in addition to environmental monitoring, waste collection, and street lighting control. For example, machine learning algorithms can process traffic data and, over time, learn to predict accidents before they happen to save lives, or process energy data and similarly predict power outages and use relevant models for power usage to smooth out peaks. Armed with such information, data-driven smart sustainable cities of the future can re-engineer streets and traffic signals, energy systems, and distribution networks, and take pre-emptive actions. The increasing adoption of AI is expected to continue, so is its impact on the different aspects of sustainability. However, AI must not be the sole focus of future cities due to the risk of losing human dimensions.

4.1.8 Software engineering

Software engineering is the systematic application of engineering approaches to the development, design, implementation, testing, operation, improvement, maintenance, and documentation of complex software. According to Sommerville (2007, p. 7), "Software engineering is an engineering discipline that is concerned with all aspects of software production from the early stages of system specification to maintaining the system after it has gone into use." Engineering computer applications software and computer systems software are at the heart of data-driven smart sustainable urbanism with respect to applied technology solutions and their implementation in operative management and development planning. Such solutions are associated with many computer applications software and computer systems software spanning many urban systems, including smart grids, smart meters, smart environmental monitoring systems, smart waste collection systems, smart street lighting systems, smart transport systems, smart traffic systems, smart urban metabolism models, and smart healthcare systems, just to name a few. They are also involved in city operating systems and city operations centers. Our urban everydayness is entangled with data sensing, data processing, and communication networking, and our wired and connected world generates and analyzes overwhelming and incredible amounts of data. Modern cities are turning into constellations of instruments across many scales and thus being reduced to algorithmic and calculative procedures and morphing into a haze of software instructions. These are becoming essential to urban operational functioning, planning, and management.

4.2 Data science

Data science is largely seen as the umbrella discipline that incorporates a number of other disciplines. To put it differently, data science is the amalgamation of numerous parental disciplines. As an example of capturing this, Blei and Smyth (2017) describe data science is "the child of statistics and computer science," where the "child" metaphor appropriately depicts that data science inherits from both its parents, but eventually evolves into its own entity. They further elaborate: "data science focuses on exploiting the modern deluge of data for prediction, exploration, understanding, and intervention. It emphasizes the value and necessity of approximation and simplification; it values effective communication of the results of a data analysis and of the understanding about the world and data that we glean from it; it prioritizes an understanding of the optimization algorithms and transparently managing the inevitable tradeoff between accuracy and speed; it promotes domain-specific analyses, where data scientists and domain experts work together to balance appropriate assumptions with computationally efficient methods."

As an interdisciplinary field, it employs theories, methodologies, and practices from across several fields within the context of statistics, mathematics, computer science, information science, and data engineering while morphing them into a new discipline. Computer science focuses more heavily on the theory and mathematical foundations that serve as a basis for programming languages, whereas information science is primarily concerned with analysis, collection, classification, manipulation, storage, retrieval, dissemination, and protection of information. Computer information systems focus more on solving practical problems or improving processes with computing technology. The practical engineering goal of data science: actionable knowledge extracted from large bodies of data and consistent patterns for generating predictive models, takes it beyond traditional approaches to analytics, e.g., the statistical methods that have prevailed over several decades were originally designed to perform data–scarce science, i.e., to identify significant correlations and relationships from small, clean sample data sizes with known attributes. The future of data science not only exceeds the boundary of statistical theories in scale and methodology, but data science will revolutionize current academia and research paradigms (Donoho, 2015).

Data science is often said to include particularly the allure of big data, the fascination of unstructured data, the advancement of data–intensive techniques and algorithms, and the precision of mathematics and statistics. It employs scientific methods, systems, processes, and algorithms to extract useful knowledge and valuable insights from large masses of data in various forms using a set of analytics techniques, such as data mining and pattern recognition, statistical analysis, data visualization and visual analytics, and prediction and simulation modeling. These analytics techniques rely on machine learning (artificial intelligence) techniques and huge computational power to process and analyze data. Recent years have witnessed a remarkable progress with regard to handling big data and performing sophisticated analytics, and these have been utilized in urban science (e.g., Batty et al., 2012; Bibri, 2019e; Kitchin, 2016). Big data entail a wide spectrum of observational data generated through transactional, operational, planning, and social activities that are not specifically designed for research. Their use for research and analysis becomes significantly complicated as a result of the structure and access conditions associated with the ever-increasing deluge of data in the urban context. New sources of data are rapidly emerging as a result of technological, institutional, economic, environmental, and social innovations.

Data science is a flourishing field, and its particular concerns are relatively new and its general principles are just evolving. Its ultimate goal is to enhance decision–making pertaining to a large number and variety of domains across many fields through the practice of data analytics—data–driven decision–making (DDD). Yet, data science requires a careful thinking about what kind of available data might be used and how these data can be used in relation to a given application domain, specifically in terms of the problem that is to be tackled (Bibri & Krogstie, 2018). It assumes access to and utilization of large masses of data, and often benefits from sophisticated data engineering facilitated by data processing and other software technologies being in use within a wide variety of organizations and institutions. In light of the above, it becomes clear why several terms have become muddled, confused, mixed–up, and interchanged in the world of big data. They overlap and interweave with one another, but are still quite distinct. Ultimately, it becomes necessary to understand the purpose, value, and scope of each term so as to give the terms their real meaning, as all play an integral part in the world of big data.

In the context of data-driven smart sustainable urbanism, data science involves a set of unified concepts, principles, processes, and techniques as fundamentals that are incorporated in cutting–edge technologies distributed across diverse urban domains for understanding, explaining, and predicting urban processes and problems in relation to the environmental, economic, social, and physical aspects of sustainability via the automated analysis of the deluge of urban data, coupled with specialized knowledge, creativity, and common sense of urban data analysts or scientists. Accordingly, data–science oriented analytic thinking enables one to evaluate urban sustainability proposals for data mining projects in the context of data-driven smart sustainable cities. If a planner, strategist, or expert proposes to improve a particular energy, transport, traffic, environment, or healthcare application by extracting useful knowledge from urban data, it is crucial for the data analyst to be able to assess the proposal systematically and decide whether and why it is sound or flawed. This concerns identifying weak spots, unrealistic assumptions, and unconnected and missing pieces rather than determining whether it will actually succeed.

The fundamentals of data science incorporated in data science technologies underlie the functioning of big data analytics, e.g., data mining as a process of extracting useful knowledge from large masses of data for enhancing decision–making and generating deep insights. In organizing thinking and analysis, these fundamentals make it possible to deeply understand data science approaches instead of focusing in depth on the wide range of specific data mining algorithms (Provost & Fawcett, 2013). Compared to other big data analytics techniques, coupled with the fact that data science is of a wider application than the use of data mining, data mining algorithms provide the most explicit illustrations of data science fundamentals, which differ from, and are complementary to, statistics and database querying. However, in the context of data-driven smart sustainable urbanism, it has become important to foster the ability to approach urban sustainability problems 'data–analytically,' as well as to assess how urban data can improve sustainability performance in relation to diverse urban domains. This implies that the knowledge extracted from large bodies of urban data is assumed to be in the form of nontrivial, actionable models. This entails applying a set of fundamental concepts that facilitate careful urban data-analytic thinking, understanding data mining techniques and data science applications in relation to sustainability dimensions, and developing relevant frameworks for structuring urban thinking about data analytics (sustainability) problems so that it can be done systematically.

Currently, the data in those disciplines and applied fields that have lacked solid theories, like the social sciences and related disciplines, could be utilized to generate powerful predictive models. Cleveland (2001) urges prioritizing the extraction of applicable predictive tools over explanatory theories from colossal amounts of data.

For the future of data science, Donoho (2015) projects an ever-growing environment for open science where data sets used for academic publications are accessible to all researchers. Open science also involves making scientific research available to all levels of an inquiring society, as well as disseminating, sharing, and developing knowledge through collaborative networks. The scope and impact of data science will, as concluded by Donoho (2015), continue to enormously expand in the upcoming decades as scientific data and data about science itself become overwhelmingly abundant and ubiquitously available. Already, significant progress has been made within data science, information science, computer science, and complexity science with respect to handling and extracting knowledge and insights from big data and these have been utilized within urban science.

4.3 Data–intensive science

Having emerged as a result of the recent advances in big data science and analytics and the underpinning technologies, data-intensive science is instigating a radical change in every scientific discipline. With this fourth paradigm of science, everything about science is changing because of the impact of the ever-increasing deluge of data and the advancement of data analytics techniques. In data-intensive scientific discovery, the mining and exploration of scientific data is intended to unify theory, simulation, and experimental verification. Data–intensive science is a data–driven, exploration–centered form of science, where big data computing and the underpinning technologies are heavily used to help scientists and scholars manage, analyze, and share data for multiple purposes (Bibri, 2019e). As an epistemological or paradigmatic shift, it involves mainly two positions. The first position is a form of inductive empiricism in which the data deluge, through analytics as manifested in the data being wrangled through an array of multitudinous algorithms to discover the most salient factors concerning complex phenomena, can speak for itself free of human framing and subjectivism and without being guided by theory (as based on conceptual foundations, prior empirical findings, and scientific literature). As argued by Anderson (2008), "the data deluge makes the scientific method obsolete' and that within big data studies 'correlation supersedes causation, and science can advance even without coherent models, unified theories, or really any mechanistic explanation at all." This relates to exploratory data analysis which may not have pre–specified hypotheses, unlike confirmatory data analysis which is used in the traditional way of doing science that does have such hypotheses. The second position is data–driven science, which seeks to generate hypotheses out of the data rather than out of the theory, thereby seeking to hold to the tenets of the scientific method and knowledge–driven science (Kelling et al., 2009, p. 613). Here, the conventional deductive approach can still be employed to test the validity of potential hypotheses but on the basis of guided knowledge discovery techniques that can be used to mine the data to identify such hypotheses. It is argued that the data–driven science will become the new dominant mode of scientific method in the upcoming Zettabyte Age because its epistemology is suited to exploring and extracting useful knowledge and valuable insights from enormous, relational datasets of high potential to generate more holistic and extensive models and theories of entire complex systems rather than parts of them, an aspect which traditional knowledge–driven science has failed to achieve (Kelling et al., 2009; Miller, 2010).

In recent years, big data science and analytics has brought about a radical change in the basic concepts, theories, assumptions, and experimental practices of science—thought patterns or ways of reasoning within the ruling theory of science, marking a paradigm shift from the dominant scientific way of looking at the world. The current model of reality, which has dominated a protracted period of puzzle–solving, is undergoing a sudden epistemological break with wide–ranging societal implications. The history of science has shown that the turbulence that sets in can lead to a paradigm shift that takes place over varied periods of time. Kuhn (1962) suggests that the history of science can be divided up into times of normal science and briefer periods of revolutionary science. The author characterizes normal science (when scientists add to, elaborate on, and work with a central, accepted scientific theory) as the process of observation and puzzle solving that takes place within a paradigm, whereas revolutionary science occurs when one paradigm overtakes another in a paradigm shift (e.g., Bird & Zalta, 2013). Data-intensive science is taking an identifiable form and increasingly gaining its own new followers, which are currently in the phase of intellectual conflict with the hold-outs of the old paradigm of science (Bibri, 2019e). In this regard, this new scientific truth is not only making its opponents see the light, but eventually die, manifested in the new generation of data science advocates growing up that is familiar with this truth. In addition, the rationale for the choice of the data-intensive approach to science as an exemplar is a specific way of viewing the current reality, where this view and the status of this exemplar are mutually reinforcing. This paradigm shift in science is so convincing that normally renders the possibility of new epistemological alternatives intuitive, thereby not obscuring the possibility of the existence of other imageries that are hidden behind the current paradigm of science. Besides, the conviction that the current paradigm of science is reality tends to disqualify evidence that might undermine the paradigm of science itself, which leads to a build-up of reconciled inconsistencies and anomalies that are determined to accumulate, and thus cause a paradigm shift in science. This is responsible for the eventual revolutionary overthrow of the incumbent paradigm of science, and its replacement by a new one (Kuhn, 1962). Yet, the acceptance or rejection of a paradigm is a social process as much as a logical process, an argument that relates to relativism: the idea that knowledge and truth exist in relation to culture, society, or historical context, and are not absolute, or that views are relative to differences in perception and consideration. There is no universal, objective truth according to relativism; rather, each point of view has its own truth. Kuhn (1962, p. 170) denies the accusation of being a relativist later in his postscript: scientific development is "a unidirectional and irreversible process. Later scientific theories are better than earlier ones for solving puzzles… That is not a relativist's position, and it displays the sense in which I am a convinced believer in scientific progress."

4.4 Urban science

As a result of the increasing prevalence and widespread development of smart cities and the growing application and use of big data analytics, the definition of urban informatics has become narrow and limited. As an example, Thrift (2014b) describes urban informatics as big data analytics for efficiency and productivity gains in city contexts, unless the arts and social sciences are added to the interdisciplinary mix. This particular specialization within urban informatics has been referred to as urban science (Batty, 2013) or "data–driven, networked urbanism" (Kitchin, 2015). Accordingly, it is not uncommon that urban informatics and urban science are used interchangeably as they do overlap in many aspects. However, the strong recursive relationship between urban science and data–driven urbanism lies in that the former provides the fundamental ideas and the key tools to enact city analytics and data–driven decision–making, and the latter provides the applied domain and raw material (Kitchin, 2016).

Urban science is an interdisciplinary field within which data science is practiced. Its ultimate goal is to enhance decision–making pertaining to a large number and variety of urban domains through the practice of big data analytics. Positioned at the intersection of science and design, urban science draws on new disciplines in the natural science and information science, and seeks to exploit the development of modern computation and the growing abundance of data. As a research field, it is concerned with the study of diverse urban issues and problems, and thus aims to produce both theoretical and practical knowledge that contributes to understanding and solving them in contemporary cities. In this respect, it entails making sense of cities as they are by identifying relationships and urban laws, as well as predicting and simulating likely future scenarios under different conditions, potentially providing valuable insights for planning and development decision–making and policy formulation (Kitchin, 2015). As such, it involves data–analytic thinking and computational modeling and simulation approaches to exploring, understanding, and explaining urban processes, and also addressing several challenges posed by urban data. The two fundamental ones are: (1) how to handle and make sense of billions of observations that are being generated on a dynamic basis (Batty et al., 2012) and (2) how to translate the insight derived into new urban theory (fundamental knowledge) and actionable outcomes (applied knowledge) (Batty, 2013; Foth, 2009; Ratti & Offenhuber, 2014). In this respect, urban science radically extends quantitative forms of urban studies, blending in data science, social physics, and geo–computation (Batty, 2013). The new urban science—which is underpinned by urban sustainability science, a transdisciplinary field that integrates and fuses theories from urban sustainability and sustainability science—seeks to make cities more sustainable, resilient, efficient, livable, and equitable by rendering them more measurable, knowable, and tractable in terms of their operational functioning, management, planning, development, and governance (Bibri, 2019e).

4.5 Modeling and simulation

Modeling and simulation is an emerging discipline that is based on developments in diverse areas of computer science. It is also influenced by developments in complexity science, data science, urban science, systems engineering, and systems theory. This foundation brings together elements of art, science, engineering, and design in a complex and unique way that requires domain experts to enable appropriate decisions when it comes to the application and use of modeling and simulation methods within the domain of data-driven smart sustainable urbanism.

The concepts of modeling and simulation are often used interchangeably, or as synonyms within disciplines. Within the emerging discipline of modeling and simulation, however, these two concepts are treated as distinctive and of equal importance. Modeling is understood as the purposeful abstraction of reality, resulting in the formal specification of a conceptualization and the underlying assumptions and constraints. Simulation denotes the production of a computer model of something. Modeling and simulation involve models that are used to support the implementation of an executable version on a computer over time. Modeling focuses mainly on the conceptualization aspects and simulation mainly on the implementation aspects. In more detail, modeling and simulation is the use of models—e.g., physical, mathematical, or logical representation of a system or process—as a basis for simulations—i.e., computational methods for implementing a model to develop data as a basis for decision–making pertaining, for example, to planning, design, and operational functioning.

One of the existing taxonomies of modeling and simulation that is of relevance to data-driven smart sustainable city planning, design, and operational functioning includes:

- Analyses support is conducted in support of urban planning. Very often, the search for an optimal solution (e.g., integration of urban design principles with data-driven smart technology solutions to advance sustainability) that shall be implemented is driving these efforts. What–if analyses of alternatives fall into this category as well. This sort of work is often accomplished by simulysts. A special use of analyses support is applied to urban operations. Simulation methods improve the functionality of decision support systems by adding the dynamic element, and also allow to compute estimates and predictions, including optimization and what–if analyses.
- Systems engineering support is applied for the design, development, and testing of systems (energy, transport, traffic, etc.). It can start in early phases and include topics like executable system architectures. And it can support testing by providing a virtual environment in which tests can be carried out. This type of work is often accomplished by engineers and architects.

Modeling and simulation are of high importance and relevance to the domain of data-driven smart sustainable urbanism. Representing the real system of data-driven smart sustainable cities of the future using computational models that allow modelling and simulating its dynamics and changes allows exploring its behavior in an articulated way, which would otherwise be not possible, too expensive to deploy, or too risky in the real-world setting. Modeling and simulation are a key enabler for engineering activities and operations associated with complex systems, such as data-driven smart sustainable cities in terms of its design and development. A collection of applicative modeling and simulation methods to support systems engineering activities is provided in (Gianni, D'Ambrogio, & Tolk, 2014). The computational representation of the system of data-driven smart sustainable cities of the future enables engineers, designers, and planners to reproduce the underlying behavior and act upon the outcome in ways that enhance and optimize its designs and thus operational functioning and management.

Building simulation and prediction methods on top of the patterns and models generated through the process of big data analytics as part of a holistic system for the city is intended to deal with both short-term and long-term issues in the context of sustainability. Simulation models help predict potential changes so that the risks and contingencies that might arise through city planning can be avoided or mitigated, and that the implementation and testing costs following city design and development can be significantly reduced, especially for new cities. One of the significant challenges pertaining to data-driven smart sustainable urbanism is the construction of new powerful forms of simulation models that embrace the concept of the city as a complex, multifaceted, dynamic, and contingent system. That is to say, a new class of simulation models that simulate various activities in the city that will evolve as its structures themselves evolve and become smarter as to their contribution to sustainability. This relates to city dynamics as self-organizing evolution processes in the sense of forces or properties which stimulate growth, development, or change within the city system.

Regarding the human capacity to predict the behavior of complex systems through modeling, it is believed that the sciences of complex phenomena cannot be modeled after the sciences that essentially deal with simple phenomena. This argument is particularly associated with chaotic systems whose long–term behavior remains difficult to forecast with accuracy. Prigogine (1997) argues that complexity gives no way whatsoever to precisely predict the future. Nonetheless, one can theoretically make accurate predictions about the city on the basis of the kind of knowledge that is as good as it is possible in regard to the relevant equations describing its behavior. Hayek (1978) explains that complex phenomena can only allow pattern predictions using modeling approaches, compared to the precise predictions pertaining to non – complex phenomena. The former is at the core of the simulation models that are intended to translate the structure of the city into a set of equations characterizing the nature of the underlying relationships and their direction and strength, predicated on the assumption that the set of reciprocal relationships pieced together generate the patterns of behavior exhibited by the city. The whole idea is still unfeasible in practice at the current stage of research in complexity science and its application in data-driven smart sustainable urbanism.

The use of computer simulation is primarily intended to stimulate applied research in the simulation of the adaptive behavior of the city due to the underlying web of reciprocal relationships that cycle to generate the kind of behavioral patterns that its overall system exhibits as a manifestation of the interaction and cooperation between different constituent components as nested systems in themselves and representing networks of networks. In this regard, the simulation of the adaptive behavior of the city on a computer system necessitates ensuring that the set of the reciprocal relationships involved generate the patterns of behavior that its overall system exhibits. Important to consider additionally are the mechanisms believed that the city uses to control itself. The basic idea is to explore how things are related to and affect each other, and how they are connected to, configured in, and constrained by the diverse subsystems forming the city system in terms of pressures and expectations. The ultimate aim is to design, build, and manage the control systems of engineering solutions enabled by big data technology in such that they can proliferate and increase in size and connectivity in response to urban growth, environmental pressures, changes in socio–economic needs, discontinuities, and transitions. Many real complex systems, including cities, have the potential for radical qualitative changes while retaining systemic integrity. However, the adaptive behavior of the city is inherently impossible to fully model computationally, irrespective of the amounts of data available and the level of data velocity due to the kind of relationships between the dynamically increased number of its internal sub–systems and between these and their external environment. Such behavior has distinct properties that arise from the nature of these relationships given that it integrates different models of urbanism with their own designed complex systems (i.e., compact, ecological, and technological).

The commonalities among complex systems as they appear in a wide variety of disciplines or emerging fields, including data-driven smart sustainable urbanism, have become the topic of their own independent area of research. A deeper understanding of the dynamical properties and processes of complex systems is crucial to bringing about a drastic change to both the simulation models that we are able to build based on the analysis of big data deluge of various velocities (especially real–time data) and at different spatial scales and over different time spans, as well as to the way in which the underlying technologies can inform planning and decision processes. Such properties are at the core of the new conceptions of the way the city functions and thus can be planned and designed. Specifically, as a set of interacting subsystems, the city should be built to be scalable, robust, resilient, stable, and balanced by incorporating such dynamical properties as self–organization, emergence, adaptation, feedback loops, spontaneous order, nonlinearity, and evolution. On the whole, what is crucially important in the quest for making the city function as a social organism is deeper and broader knowledge on how complex systems function and its effective incorporation in the very design, engineering, and modeling of the technological systems intended to monitor, understand, analyze, and plan the city for achieving the desired outcomes. Especially, complexity science brings together deep scientific questions pertaining to sustainability with application–driven goals.

4.6 Complexity science and complex systems

Complexity science is a set of conceptual tools and theories from an array of disciplines (Benham-Hutchins & Clancy, 2010; Paley & Gail, 2011). It deals with complex systems as a collection of interconnected parts that are dynamical, unpredictable, and multidimensional in nature. It has been discussed in both natural and social sciences. In a wide range of related complex systems, computational modeling, as based on mathematical developments and modeling approaches from physics, is undertaken to study the behavior of complex systems to better understand them. Software engineering expertise can be used to apply new results as well as to inspire new approaches in this regard (Batty et al., 2012).

As an emerging approach to research, complexity science is the scientific study of complex systems, systems composed of many parts connected and joined together by a web of relationships that interact to generate collective behaviors which cannot easily be explained on the basis of the interaction between those parts as individual constituent elements. In this respect, complexity entails the way a vast number of complicated and dynamic sets of relationships, interactions, or dependencies can produce some behavioral patterns. Complexity science is integral to the understanding of data-driven smart sustainable cities, which is a moving target in that they are becoming more complex through the very technologies being used to understand them.

As an approach to science, complex systems investigates how the relationships, interactions, or dependencies between the parts of a system give rise to its collective behavior, and how it interacts and forms relationships with its environment (Yaneer, 2002). Thus, it is principally concerned with the behaviors and properties of systems. As a research approach, it deals with problems in many different disciplines, including information theory, computer science, mathematics, statistical physics, biology, ecology, nonlinear dynamics, sociology, and economy. As an interdisciplinary field, it draws on theoretical contributions and perspectives from these disciplines, e.g., spontaneous order from the social sciences, chaos from mathematics, cybernetics from technology, self–organization from physics, adaptation from biology, and many more others. Worth pointing out is that complex systems are characterized by nonlinearity and indeed require more than simplistic linear thinking as they feature a large number of interacting elements (patterns, agents, processes, etc.) whose aggregate activity (behaviors, relationships, interactions, etc.) does not emanate from the summations of the activity pertaining to the individual elements. As such, they typically exhibit hierarchical self–organization under some kind of selective pressures. Examples of complex systems include cities, ecosystems, organisms, global climate, neural network, human brain, ICT network, and the entire universe. In relation to cities, Bibri (2018a) systematically explores, based on complexity science and systems thinking as theoretic approaches, the key structures, behavioral patterns, dynamic properties, relationships, interactions, and dependencies underlying data-driven smart sustainable cities as complex systems and dynamically changing environments. The author also discusses the potential of big data analytics and related urban intelligence functions and simulation models for improving and advancing the process of sustainable urban development. Advanced ICT is founded on the application of complexity theory to urban systems in terms of tracking changing dynamics, disentangling intractable issues, and tackling complex challenges. Urban systems are becoming ever more complex through the technologies being used to understand them. Besides, complex systems cannot be understood and studied without the use of sophisticated computational and data analytics. In light of this, complexity science is linked to many different disciplines and professional fields that have cities as their concern. Cities can only be studied in an interdisciplinary context, and the perspective here involves developing a social physics and data–driven science of cities that are consistent with treating their structure and evolution as complex systems.

The concerns that complexity science addresses have grown out of numerous investigations from a varied intellectual ancestry, including cybernetics, general systems theory, chaos theory in dynamical systems, complex systems, mathematical systems, and complex adaptive systems (social systems, urban systems, etc.) where the parts actively change the way they interact. The increased use of computer simulation created research in the simulation of adaptive behavior in the 1990s. From 2000s and onward, complexity science has taken stock of what has been accumulated as substantive knowledge of all this rich background of work. A key part of the current emphasis of complexity science is its application to practical technological and engineering systems in that control systems need to be designed, managed, and constructed as they proliferate and increase in size and connectivity in a variety of contexts, e.g., control systems associated with data-driven smart sustainable cities. It is desirable to have the ability to build systems that are scalable, robust, and adaptive by using such properties as self–organization, self–adaptation, self–regulation, self–repair, and evolution as a way of mimicking biological systems. Complexity science is a subject of study that is well positioned to bringing together deep scientific questions pertaining to sustainability and urbanization with driven-driven solutions goals within the field of data-driven smart sustainable urbanism. Its contemporary applications are complemented by a rich background of theoretic work.

Complexity science touches on all facets of science and technology, creating an array of multitudinous new opportunities within numerous research domains. Important to underscore in this context is that complexity is not just determined by the large number of parts of a system with very intricate design, but also by such dynamical properties as self–organization, adaptation, emergence, feedback loops, and nonlinearity. In the context of data-driven smart sustainable cities, technological and engineering systems based on big data analytics are primarily designed to minimize these tricky dynamical properties. These can otherwise make such cities difficult to design, predict, and control. However, if desirable emergent behaviors and processes can be managed, harnessed, and exploited, they can allow to move beyond the limits of conventional technological and engineering systems that are merely complicated. Apart from that, we are dealing with the traditional approach to tackling complexity, which aims to reduce or constrain it and thereby typically involves compartmentalization: dividing a large system into separate parts. Technological and engineering systems are susceptible to failure for they are often designed using modular components, and where failure usually results from the potential issues arising to bridge the divisions.

Concerning the question of where complexity science is headed, the recent trends in this scientific discipline are bringing together research from a variety of established disciplines, including computer science, data science, data-intensive science, sustainability science, mathematics, complex adaptive systems, systems biology, systems ecology, environmental sciences, systems engineering, physics, and management towards new developments with wide–ranging implications. This is to stimulate new research opportunities and create new research directions and innovative cross–disciplinary activities. Indeed, the push from academia and industry to solve complexity challenges pertaining to modern cities and other complex systems in a variety of fields has produced a massive response from the academic community and several research funding councils across the globe. One of the most enticing aspects of complexity science is its interdisciplinary and transdisciplinary nature. Important to underscore in this regard is the interface of complexity science with organismic biology, cellular biology, molecular biology, and ecology, in addition to many different disciplines. This involves fascinating possibilities to learn from how complex adaptive systems cope with emergent dynamical behaviors and properties, as well as to adapt to, control, harness, and exploit them in every possible way to be thought of. Indeed, a lot of research in complexity science spanning diverse domains, including data-driven smart sustainable urbanism, is seeking ways to understand, analyze, model, and extract the useful properties and behaviors of biological systems using big data analytics for applied purposes related to planning, design, and development. This offers the prospect of better understanding complex systems and gaining inspiration for new approaches into solving the technological and engineering challenges associated with human systems in terms of control, management, optimization, resilience, robustness, and prediction. Among the systems from ICT that need new approaches inspired by biological systems to handling complexity in the context of data-driven smart sustainable cities include, but are not restricted to, the following:

- Large–scale software development
- Data processing and management systems
- Database management and integration
- Sensor networks
- Infrastructure networks
- Semantic web
- Cloud and fog computing
- Grid and distributed computing
- Wireless network reconfiguration
- Telecommunication systems and Internet networks.

The inspiration can emanate from the various characteristic features of biological systems, including evolution dynamics, DNA and self–replication, metabolic networks, gene regulation networks, ecosystem sustainability, and immune systems and repair. The relevant topics that help connect the biological inspiration with the challenges pertaining to technological and engineered systems include, but are not limited to, network science, dynamical systems, feedback control, machine learning, statistical theory of complex systems, information theory, evolutionary design and algorithms, self–organization and –regulation, simulation modeling, and data mining and time series analysis.

For example, in terms of complexity and network science, complex systems can be represented by a network where nodes represent the components and links represent their interactions (Dorogovtsev & Mendes, 2003; Newman, 2010). Examples in this regard relate to ICT networks, infrastructure networks, urban networks, socioeconomic networks, biological networks, and neural networks. Networks as parts of complex systems can fail and recover spontaneously (see Majdandzic et al., 2013 for modeling this phenomenon). Interacting complex systems can be modeled as networks of networks (e.g., Gao, Buldyrev, Stanley, & Havlin, 2011 and Majdandzic et al., 2016 for their breakdown and recovery properties).

4.7 Sustainability science

The link between sustainable development and science stems from the idea that the former is an aspiration that should, as realized by several scholars over the past decade, be achieved only on the basis of scientific knowledge. This has justified the establishment of a new branch of science due to the fact that, arguably, humanity is confronted at an ever unprecedented rate and larger scale with the ramifications of its own success as a species. The way things have changed in recent years (and the attempts being undertaken to take this into account) calls for a scientific approach to understanding the underlying web of ongoing, reciprocal relationships in the process of cycling to generate the patterns of behavior that the ecosystems are exhibiting, and to figure out the mechanisms these ecosystems are using to control themselves. The point is that the complexities, uncertainties, and hazards of the human adventures are triggering unprecedented changes increasingly requiring insights from all the sciences to tackle them if there is a shred of seriousness about the aspiration to enhance and sustain the quality of life. The real challenge emanating from the fragmented character of science lies in understanding and acting upon the causal mechanisms and behavioral patterns in response to the reciprocal relationships between different complex systems across several time and space scales. This calls for fusing disciplines, a transdisciplinary approach that reconciles and amalgamates the theoretical and practical knowledge, the quantitative and qualitative perspectives, and the natural and social sciences. Sustainability science is what such an integrative approach entails, and whose emphasis is on understanding changes in states rather than just their characterization. Systems theory and system analysis approaches have become the most coherent expression of this insight (Bossel, 2004). Sustainability science is perhaps the most clear and desirable illustration of the endeavor of reinforcing the unified approaches and unifying tendencies in science, as well as of liberating the study of real-world processes from the boundaries between the scientific disciplines (de Vries, 2013).

Sustainability is a relatively new area of science that focuses on explaining and understanding the dynamic interactions of socio–ecological systems, of which the city represents a clear illustration and perfect example. It holds much promise as an approach to dealing with the kind of wicked problems and intractable issues pertaining to city planning and development. Sustainability has theoretical foundations and assumptions from which it has grown that have solidified it into a defined science which centers on general truths and laws, as well as on scientific methods of enquiry. As a flourishing scientific discipline, sustainability science has emerged in the early 2000s (e.g., Clark, 2007; Clark & Dickson, 2003; Kates, Clark, Corell, Hall, & Jaeger, 2001; Lee, 2000). As with the definition of sustainability, a consensual definition of sustainability science is difficult to pin down. Kieffer et al. (2003, p. 432) define sustainability science as "the cultivation, integration, and application of knowledge about Earth systems gained especially from the holistic and historical sciences...coordinated with knowledge about human interrelationships gained from the social sciences and humanities, in order to evaluate, mitigate, and minimize the consequences...of human impacts on planetary systems and on societies across the globe and into the future." As an interdisciplinary and transdisciplinary field, it mixes and fuses disciplines across the natural sciences, social sciences, and applied and engineering sciences. The philosophical and analytic framework of sustainability draws on and connects with numerous different disciplines and fields. Sustainability is studied and examined in various contexts of environmental, social, economic, and cultural development, and also managed over many temporal and spatial scales. The focus ranges from macro levels starting from the (sustainability) of planet Earth to the sustainability of societies, regions, cities, and neighborhoods, as well as economies, ecosystems, and communities, and to micro levels encompassed in buildings and individual lifestyles.

As a research field, sustainability science probes the complex mechanisms involved in the profound interactions between environmental, economic, and social systems to understand their behavioral patterns and changing dynamics in order to create upstream solutions for tackling the complex challenges associated with the systematic degradation of the natural system and the concomitant perils to human well–being, the challenges that imperil the integrity of the planet's life support systems and compromise the future of human life. It is concerned with advancing knowledge on how the natural and human systems interact in terms of the underlying reciprocal relationships for the purpose of designing, developing, implementing, evaluating, and constantly optimizing and enhancing human engineered systems as practical solutions and interventions that support the notion of the socio–ecological system in balance and nurture and sustain the linkages between scientific research and technological innovation and policy and public administration processes in relevance to sustainability. In concrete terms, sustainability science focuses on the interactions between the resource system, the human system, and the governance system to identify and solve potential problems through devising and implementing holistic solutions. This research field seeks to give the 'broad–based and crossover approach' of sustainability a solid scientific foundation. It also provides a critical and analytical framework for sustainability (Komiyama & Takeuchi, 2006), and "must encompass different magnitudes of scales (of time, space, and function), multiple balances (dynamics), multiple actors (interests), and multiple failures (systemic faults)" (Reitan, 2005, p. 77). In addition, sustainability science can be viewed as "neither basic nor applied research but as a field defined by the problems it addresses rather than by the disciplines it employs; it serves the need for advancing both knowledge and action by creating a dynamic bridge between the two" (Clark, 2007, p. 1737).

From a broader perspective of sustainability science, some views highlight the need to probe the root causes of the fundamental unsustainability of the predominant paradigms of technological, economic, and societal development. In this line of thinking, Bibri (2015) provides an analytical account of the implications of ICT of pervasive computing as a form of advanced science and technology for environmental and societal sustainability. Sustainability science must involve the role of technology both in exasperating the unsustainability of social practices as well as in tackling the problems they generate, in addition to including the study of the societal structures as to material consumption (e.g., Brown, 2012).

To grasp the integrated whole of the socio–ecological system to tackle the underlying problems necessitates global political consensus and collaboration between social, economic, scientific, and technological disciplines in terms of scholars and practitioners, as well as the active engagement of citizens, communities, organizations, and institutions. One of the key missions of sustainability science as a more disciplined framework is to aid in coordinating cross–disciplinary integration as a critical step towards a global joint effort and concerted action. In addition, the way in which sustainability science as a scholarly community can best contribute to the understanding and implementation of the goals of sustainable development should be based on an in–depth critical analysis and evaluation through scenario analysis, scientific research, technological innovation, stakeholder relationships, participatory decision-making, and policy recommendations and impacts. To achieve these goals, in short, requires taking an all–inclusive approach by mobilizing diverse actors, factors, and resources in the same direction, which is a daunting endeavor to undertake.

4.8 Urban sustainability science

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.

The objective of urban sustainability is to uphold the changing dynamics and thus reciprocal relationships (within and across levels and scales) that maintain the ability of cities to provide not just life–supporting, but also life–enhancing, conditions, exhibited by their collective behavior as complex systems. To achieve this, the city should work towards enhancing the underlying physical, environmental, social, and economic systems over the long run by means of sustainable interventions supported by advanced technologies and their novel applications, with the primary purpose of maintaining predictable behavioral patterns and thus stable reciprocal relationships. These typically cycle to produce the behavioral patterns that the city exhibits as a result of how it is planned, designed, and thus operate and develop. In particular, as the positive adaptation of the city depends upon how well it adjusts with the environment, it needs to make changes to protect itself and grows to accomplish its goals in terms of achieving the ultimate goal of sustainability. One way of doing this is to self–correct itself based on reactions from the environmental system with respect to climate change and related hazards and upheavals. This feature relates to the adaptive nature of complex systems in that they have the capacity to change and learn from experience, which has to do with evolutionary resilience. This denotes the ability of a system, not only to bounce back from events causing a shock through robust behavior, but also to adapt and learn from the past behaviors to surpass the previous state by extending its capacity.

To put it differently, the objective of urban sustainability can be accomplished by rendering the city processual in its conception, flexible in its planning, scalable in its design, and efficient in its operational functioning in order to be able to respond to and deal with population growth, environmental pressures, and changes in socio–economic needs, as well as to keep up with global shifts, discontinuities, and societal transitions. This involves maintaining the critical structures, key dependencies, functional integrity, resource availability, well–being, and capacity for regeneration and evolution of the city. What is important with regard to ensuring the persistence of structures and conditions necessary for keeping the city system within a preferred stability state is the need for continuous reflection as an effective way to learn from both failures and successes, as well as to achieve a deep understanding of how socio–ecological systems function to be able to work with, anticipate, and harness the underlying dynamics. This relates to what is termed as short-term planning, which can well be enabled by big data analytics. Planning across multiple time scales increase the contribution of the city to the goals of sustainable development in the long term by means of continuous reflection in the short term. "Short–termism in 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 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 city as a complex system." (Bibri, 2020e, p.16).

The quest for finding an urban planning and development approach that can accommodate the wicked problems of cities, especially in relation to sustainability and urbanization, and overcome the complexity and unpredictability introduced by socio–political factors is increasingly inspiring scholars to combine urban sustainability and sustainability science under what has recently been termed "urban sustainability science." This term is informed by urban science, a field within which data science is practiced, which in turn informs and sustains data–driven smart urbanism (Kitchin, 2016). Data-intensive science is transforming urban science and sustainability science and the way they inform and sustain urban sustainability.

While the introduction of sustainability to the goals of urban planning and development added another layer of complexity brought about by the consideration of environmental externalities and socio-economic concerns, the new urban science has opened new windows of opportunity to deal with the complex problems and conundrums in cities on the basis of modern computation and data abundance. Bibri (2019e) concludes that the new urban science—which is informed and sustained by big data science and analytics—seeks to make cities more sustainable, resilient, efficient, livable, and equitable by rendering them more measurable, knowable, and tractable. The great innovation of big data science and analytics and the underlying technologies is that the urban problems should be approached in full knowledge, which supposes a new approach to scientific development based on massive–scale data. As an evolving, systematic enterprise building and organizing knowledge in the form of explanations and predictions about the world, data–intensive scientific development entails using data–driven inductive empiricism and data–driven science. These recent epistemological approaches are at the heart of urban science (Kitchin, 2016), which informs urban sustainability science. This new science as involving complex dynamics of human–natural system interactions in cities requires a decisive, radical change in the way science is undertaken and developed. Such change is what data–intensive scientific development entails—as enabled and driven by big data science and analytics.

There are various reasons that justify the adoption of data–intensive scientific development in urban sustainability science. It is imperative for this scientific field, which focuses on understanding the dynamic interactions of the socio-ecological systems of the city, to develop and apply an advanced approach to scientific inquiry and exploration for dealing with the kind of wicked problems and intractable issues pertaining to urbanism as a set of multifaceted, contingent practices. Also, urban sustainability science should embrace data–intensive scientific development in order to be able to transform knowledge on how the natural and human systems in the city interact in terms of the underlying (changing) dynamics for the purpose of designing, developing, implementing, evaluating, and enhancing human engineered systems as practical solutions and interventions that support the idea of the socio–ecological system in balance. This embrace is additionally aimed at nurturing and sustaining the linkages between scientific research and technological innovation and policy and public administration processes in relevance to sustainability. To put it differently, the data–intensive approach to urban sustainability science is of high relevance to the cultivation, integration, and application of knowledge about natural systems gained especially from the historical sciences, and its coordination with knowledge about human interrelationships gained from the social sciences and humanities. This is of crucial importance for evaluating, mitigating, and minimizing the intended and unintended consequences of anthropogenic influences on socio-ecological systems across the globe and into the future. Another rationale for adopting data–intensive scientific development is that urban sustainability science mixes and fuses disciplines across the natural sciences, social sciences, formal sciences, and applied sciences. The analytical framework of urban sustainability science draws on and links with numerous disciplines and fields, and is studied and examined in various contexts of environmental, economic, social, and cultural development and managed over many temporal and spatial scales. In view of that, big data science and analytics can perform more effectively with respect to achieving the desired outcomes expected from the application of the interdisciplinarity and transdisciplinarity approaches to research due to the underlying analytical power, coupled with the data deluge available for scholarly inquiry or scientific exploration. This is particularly important in the context of urban science and urban sustainability for gaining new interactional and unifiable knowledge necessary for exploiting the opportunity of using advanced technologies to solve real–world problems and challenges, particularly those associated with sustainability and urbanization. In contrast to urban knowledge derived from longer standing, more traditional urban studies, big data science and analytics as practiced within the field of urban science and urban sustainability offers the potential for a new form of knowledge that is inherently longitudinal, and has greater breadth, depth, scale, and timeliness.

The solutions to the kind of wicked problems and intractable issues associated with urban sustainability are anchored in the recognition that the urban world has become more integrated, complex, contingent, and uncertain. The data–intensive approach applied to urban sustainability science is primarily meant to facilitate the link of such problems and issues to the type of problems and issues explored and probed by sustainability science through massive–data–scale analytics. The understanding of the city as an instance of socio–ecological systems based on sustainability science principles using a data–driven analytical approach can help address and overcome the challenges associated with the wicked problems and intractable issues related to urban planning and development in the context of sustainability. There is a host of new practices that sustainability science could bring to urban sustainability under the umbrella of data–intensive science, an argument that needs to be developed further and to become part of mainstream debates in urban research, practice, and policy. This argument is being stimulated by the ongoing discussion and development of the new ideas about the untapped potential of big data science and analytics for advancing sustainability science and urban sustainability, as well as merging them into a holistic framework informed by urban science and data science. Urban sustainability science as a research field seeks to give the broad–based and crossover approach of urban sustainability a solid scientific foundation. It also provides a critical and analytical framework for urban sustainability and, to draw on Reitan's (2005) view on sustainability science, must encompass different magnitudes of scales (of time, space, and function), multiple balances (dynamics), multiple actors (interests), and multiple failures (systemic faults). In addition, it should be viewed as a field defined more by the kind of wicked problems and intractable issues it addresses rather than by the academic and scientific disciplines it employs, thereby being neither basic nor applied research. As such, it serves the need for advancing both knowledge discovery and actionable decisions by creating a dynamic bridge between the two thanks to new big data analytics techniques. What will be exciting to witness in the near future is:

- how big data science and analytics will evolve and to what extent it will reshape urban sustainability science through data-intensive science;
- what kinds of new tools and techniques will be invented that would not have come into existence if not for the integration of the parental disciplines of data science, adding to the extent to which they will drastically change urban sustainability science and its applied domain: scientific smart sustainable urbanism; and
- what kinds of urban problems will urban sustainability science be able to address and solve, using more advanced big data technologies.

5 Conclusion

This paper identified, describes, discuses, evaluates, and thematically organizes the core academic and scientific disciplines underpinning the field of data-driven smart sustainable urbanism. It primarily serves to facilitate collaboration and integration between disciplines for the sheer purpose of generating the kind of interactional and

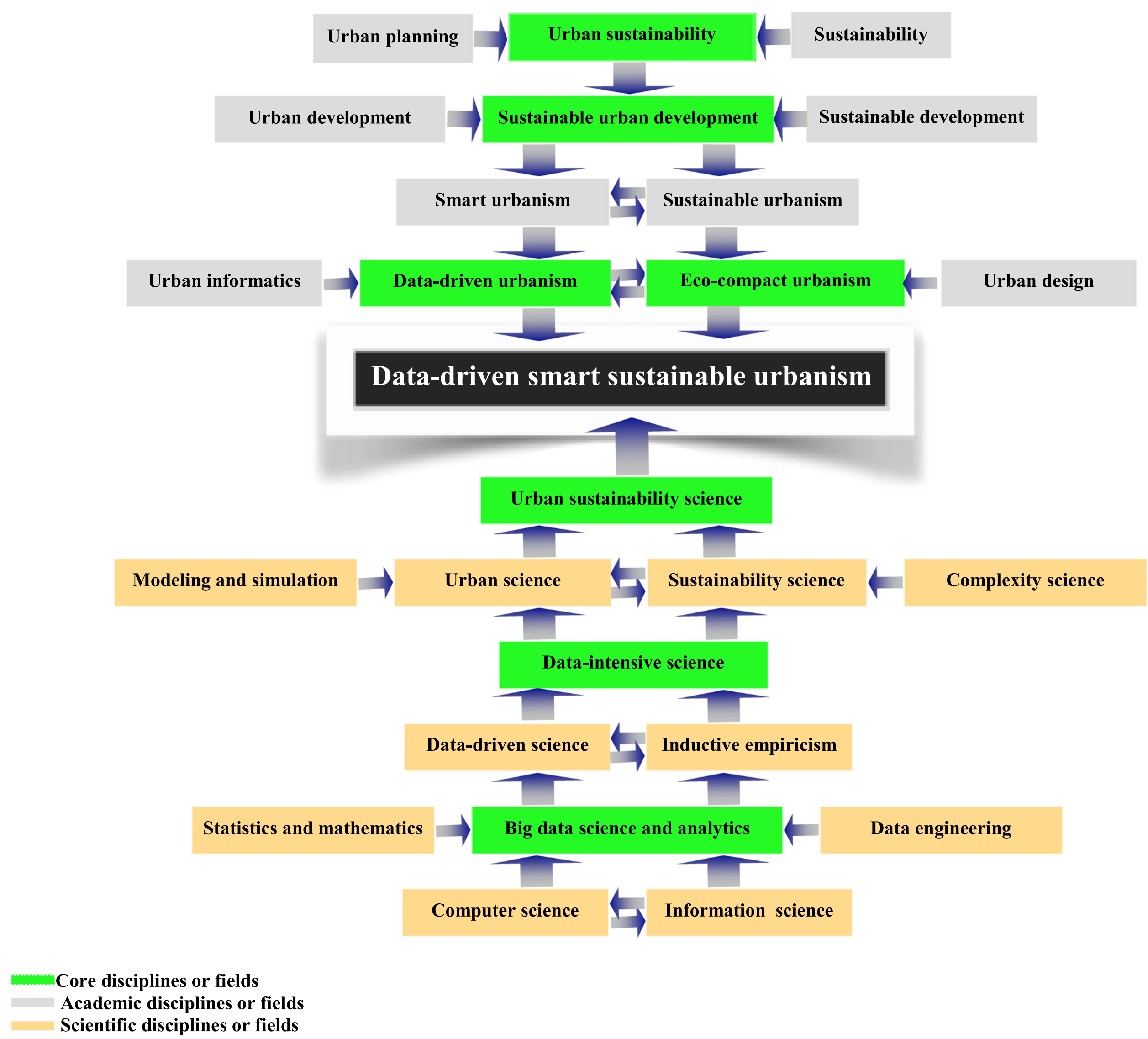

Fig. 2 An interdisciplinary and transdisciplinary framework for the core academic and scientific disciplines underlying data-driven smart sustainable urbanism

unifiable knowledge necessary for a broader and more inclusive understanding of the topic of data-driven smart sustainable urbanism (Fig. 2). This is a key contribution that supports the ethos of interdisciplinarity and transdisciplinarity characterizing the research field of data-driven smart sustainable urbanism. While the interdisciplinary perspective is about pooling approaches and insights from several disciplines and adjusting them in such that the resulting outcome becomes well suited to examining problems in this field, the transdisciplinary approach goes beyond pooling and adjusting disciplinary approaches to include their fusion to readily explore these problems in their complexity. Therefore, adopting interdisciplinary and transdisciplinary scholarly approaches in this context makes it possible to flexibly respond to the topic under study and thus uncover the best way of addressing it. Such approaches are primarily aimed at contributing to an integral reflection over where the still–emerging field of data-driven smart sustainable urbanism is coming from and where it is believed it should be headed. And how it will evolve in the upcoming decades.

This framework is intended to enable a holistic understanding of the multifaceted phenomenon of data-driven smart sustainable urbanism in terms of the underlying foundational principles. It is also meant to motivate scholars and researchers to further integrate and fuse more disciplines to create new perspectives and insights based on interactional and unifiable knowledge beyond these disciplines—with a result that yields new ideas by thinking across disciplinary boundaries and that exceeds the simple sum of each discipline. This can be accomplished by combining different analyzes, using insights and methods in parallel and conjunction, and spilling over and blurring boundaries. Pooling various disciplinary approaches together is of significance to arrive at a theoretically solid and analytically informed multi–perspectival approach to studying the topic of data-driven smart sustainable urbanism, as well as to holisticize knowledge for enhancing and rethinking related practices. Besides, interdisciplinary and transdisciplinary perspectives are necessary to address the complex issues related to this evolving approach to urbanism, and to respond knowledgeably and critically to the challenges facing sustainable cities and smart cities as regards sustainability and urbanization in the era of big data.

This work provides an important lens through which to understand the set of established and emerging disciplines that have high integration, fusion, and application potential for informing the processes and practices of data-driven smart sustainable urbanism. As such, it provides fertile insights into the core foundational principles of data-driven smart sustainable urbanism as an applied domain in terms of its scientific, technological, and computational strands.

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