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The anatomy of the data-driven smart sustainable city: instrumentation, datafication, computerization and related applications

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Abstract

We are moving into an era where instrumentation, datafication, and computerization are routinely pervading the very fabric of cities, coupled with the interlinking, integration, and coordination of their systems and domains. As a result, vast troves of data are generated and exploited to operate, manage, organize, and regulate urban life, or a deluge of contextual and actionable data is produced, analyzed, and acted upon in real time in relation to various urban processes and practices. This data-driven approach to urbanism is increasingly becoming the mode of production for smart sustainable cities. In other words, a new era is presently unfolding wherein smart sustainable urbanism is increasingly becoming data-driven. However, topical studies tend to deal mostly with data-driven smart urbanism while barely exploring how this approach can improve and advance sustainable urbanism under what is labeled 'data-driven smart sustainable cities.' Having a threefold aim, this paper first examines how data-driven smart sustainable cities are being instrumented, datafied, and computerized so as to improve, advance, and maintain their contribution to the goals of sustainable development through more optimized processes and enhanced practices. Second, it highlights and substantiates the great potential of big data technology for enabling such contribution by identifying, synthesizing, distilling, and enumerating the key practical and analytical applications of this advanced technology in relation to multiple urban systems and domains with respect to operations, functions, services, designs, strategies, and policies. Third, it proposes, illustrates, and describes a novel architecture and typology of data-driven smart sustainable cities. The overall aim of this study suits thematic analysis as a research approach. I argue that smart sustainable cities are becoming knowable, controllable, and tractable in new dynamic ways thanks to urban science, responsive to the data generated about their systems and domains by reacting to the analytical outcome of many aspects of urbanity in terms of optimizing and enhancing operational functioning, management, planning, design, development, and governance in line with the goals of sustainable development. The proposed architecture, which can be replicated, tested, and evaluated in empirical research, will add additional depth to studies in the field. This study intervenes in the existing scholarly conversation by bringing new insights to and informing the ongoing debate on smart sustainable urbanism in light of big data science and analytics. This work serves to inform city stakeholders about the pivotal role of data-driven analytic thinking in smart sustainable urbanism practices, as well as draws special attention to the enormous benefits of the emerging paradigm of big data computing as to transforming the future form of such urbanism.

Keywords: Data-driven smart sustainable cities, Data-driven smart sustainable urbanism, Big data analytics, Big data applications, Datafication, Urban science, Urban sustainability, Sustainable development, Innovation labs, Urban operation centers, Urban intelligence functions

Introduction

Contemporary cities have a key role in strategic sustainable development; therefore, they have gained a central position in operationalizing this notion and applying this discourse. This is clearly reflected in the Sustainable Development Goal 11 (SGD 11) of the United Nations' 2030 Agenda, which entails making cities more sustainable, resilient, inclusive, and safe [53]. In this regard, the UN's 2030 Agenda regards information and communication technology (ICT) as a means to promote socio-economic development and protect the environment, increase resource efficiency, achieve human progress and knowledge in societies, upgrade legacy infrastructure, and retrofit industries based on sustainable design principles [54]. Hence, the multifaceted potential of the smart city approach as enabled by ICT has been under investigation by the UN [55] through their study on 'Big Data and the 2030 Agenda for Sustainable Development.' In particular, there is an urgent need for developing and applying data-driven innovative solutions and sophisticated approaches to overcome the challenges of sustainability and urbanization. In other words, the world is drowning in data—and if planners and policymakers realize the potential of harnessing these data in collaboration with data scientists, urban scientists, and computer scientists, the outcome could solve major global challenges [12].

In recent years, there has been a marked intensification of datafication. This is manifested in a radical expansion in the volume, range, variety, and granularity of the data being generated about urban environments and citizens (e.g., [12, 33, 34, 36], with the primary aim of quantifying the whole of the city and thus putting it in a data format that can be organized, processed, and analyzed to generate useful knowledge for enhanced decision-making, as well as deep insights pertaining to a wide variety of practical uses and applications. We are currently experiencing the accelerated datafication of the city in a rapidly urbanizing world and witnessing the dawn of the big data era not out of the window, but in everyday life. Our urban everydayness is entangled with data sensing, data processing, and communication networking, and our wired world generates and analyzes overwhelming and incredible amounts of data. The modern city is turning into constellations of instruments and computers across many scales and morphing into a haze of software instructions, which are becoming essential to the operational functioning, planning, design, development, and governance of the city. The datafication of spatiotemporal citywide events has become a salient factor for the practice of smart sustainable urbanism.

Indeed, as a consequence of datafication, a new era is presently unfolding wherein smart sustainable urbanism is increasingly becoming data-driven [12]. At the heart of such urbanism is a computational understanding of city systems and processes that reduces urban life to logical and algorithmic rules and procedures, while also harnessing urban big data to provide a more holistic and integrated view or synoptic intelligence of the city. This is increasingly being directed towards improving, advancing, and maintaining the contribution of both sustainable cities and smart cities to the goals of sustainable development [12].

Overall, the new era of science and technology embodies an unprecedentedly transformative and constitutive power—manifested not only in the form of revolutionizing science and transforming knowledge, but also in advancing social practices, producing new discourses, catalyzing major shifts, and fostering societal transitions. Of particular relevance, it is instigating a massive change in the way both smart cities and sustainable cities are studied and understood, and in how they are planned, designed, operated, managed, and governed in the face of urbanization. To put it differently, these urban practices are becoming highly responsive to a form of data-driven urbanism that is the key mode of production for what have widely been termed smart sustainable cities whose monitoring, understanding, and analysis are accordingly increasingly relying on big data computing and underpinning technologies.

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

However, topical studies tend to deal mostly with data-driven smart urbanism (e.g., [7, 35–37, 40] while barely exploring how this approach can improve and advance sustainable urbanism under what is labeled 'data-driven smart sustainable cities' as a leading paradigm of urbanism [11, 12]. Moreover, research on big data applications in the context of smart cities tends to deal largely with economic growth, the quality of life, and governance (e.g., [5, 8, 15, 26, 30–33, 35, 49] while overlooking the rather more urgent issues and complex challenges related to sustainability. This paucity of research pertains particularly to the untapped potential of big data technologies and their novel applications for advancing sustainability in the context of smart sustainable cities [8]. Indeed, many of the emerging smart solutions are not aligned with sustainability goals [1]. This relates to the deficiencies and shortcomings of smart cities in this regard (see Bibri [11] for a detailed review).

Having a threefold aim, this paper first examines how data-driven smart sustainable cities are being instrumented, datafied, and computerized so as to improve, advance, and maintain their contribution to the goals of sustainable development through more optimized processes and enhanced practices. Second, it highlights and substantiates the great potential of big data technology for enabling such contribution by identifying, synthesizing, distilling, and enumerating the key practical and analytical applications of this technology in relation to multiple urban systems and domains with respect to operations, functions, services, designs, strategies, and policies. Third, it proposes, illustrates, and describes a novel architecture and typology of data-driven smart sustainable cities. I argue that smart sustainable cities are becoming knowable, controllable, and tractable in new dynamic ways thanks to urban science, responsive to the data generated about their systems and domains by reacting to the analytical outcome of many aspects of urbanity in terms of optimizing and enhancing operational functioning, management, planning, design, development, and governance in line with the goals of sustainable development.

The remainder of this paper is structured as follows. Section "Conceptual background" introduces and describes the key conceptual definitions in relevance to the topic of this study. Section "A survey of related work" provides a survey of related work. Section "Method: thematic analysis" outlines the research approach adopted in this study: thematic analysis. Section "Results and discussion" presents and combines results and discussion. As such, it delves into the heart of the data-driven smart sustainable city, covering a range of constituents and underpinnings; identifying, synthesizing, distilling, and enumerating the key practical and analytical applications of big data technology in terns of sustainability effects and benefits; discussing relevant policy and technology issues; and proposing, illustrating, and describing a novel architecture and typology of the data-driven smart sustainable city. The paper ends, in "Conclusion" section, with concluding remarks, contribution, and further research.

Conceptual background

Data-driven smart sustainable cities

'Data-driven smart sustainable cities' is a term that has recently gained traction in academia, government, and industry to describe cities that are increasingly composed and monitored by ICT of ubiquitous and pervasive computing and thus have the ability of using advanced technologies by city operations centers, planning and policy offices, research centers, innovation labs, and living labs for generating, processing, and analyzing the data deluge in order to enhance decision making processes and to develop and implement innovative solutions for improving sustainability, efficiency, resilience, equity, and the quality of life [12]. It entails developing a citywide instrumented system (i.e., inter-agency control, planning, innovation, and research hubs) for creating and inventing the future. For example, a data-driven city operations center, which is designed to monitor the city as a whole, pulls or brings together real-time data streams from many different agencies spread across various urban domains and then analyze them for decision making and problem solving purposes: optimizing, regulating, and managing urban operations (e.g., traffic, transport, energy, etc.).

Datafication

The big data revolution will transform the way we live, work, and think in the city. Datafication has become a buzzword in the era of big data revolution. This buzzword describes an urban trend of defining the key to core city operations and functions through a reliance on big data computing and underpinning technologies. In other words, the notion of datafication denotes that cities today are dependent upon their data to operate properly—and even to function at all with regard to many domains of urban life [12]. It also refers to the collective tools, processes, and technologies used to transform a city to a data-driven enterprise. In short, datafication involves turning many aspects of urban life into computerized data and transforming this information into value. As such, this concept helps better frame the changes taking place now [21]. A city that implements datafication is said to be datafied. To datafy a city is to put it in a quantified format so it can be structured and analyzed.

Cities are taking any possible quantifiable metric and squeezing useful knowledge out of it for enhanced decision-making and deep insights pertaining to many domains of urban life. Datafication entails that in a modern data-oriented urban landscape, a city's performance is contingent on having control over the storage, management, processing, and analysis of the data, as well as on the extracted knowledge in the form of applied intelligence. Tackling sustainability and urbanization issues is one of the key concerns of the datafication of the contemporary city. To put it differently, the urban world is drowning in data—and if planners and policymakers realize the potential of harnessing these data in collaboration with urban scientists and data scientists, the outcome could solve major global challenges. The point at issue is that we generate enormous amounts of data on a daily basis, a binary trail of breadcrumbs that forms a map of urban life in terms of citizens' experiences and urban dynamics, and hence the resulting disparate datasets can, if harnessed properly, open up a unique window of, and represent a goldmine, opportunity for making cities more sustainable and in tune with citizens' actual needs and aspirations.

Big data computing and the underpinning technologies

Big data computing is an emerging paradigm of data science, which is of multidimensional data mining for scientific discovery over-large scale infrastructure. Data mining/knowledge discovery and decision-making from voluminous, varied, real-time, exhaustive, fine-grained, indexical, dynamic, flexible, evolvable, relational data is a daunting challenge/task in terms of storage, management, organization, processing, analysis, interpretation, evaluation, modeling, and simulation, as well as in terms of the visualization and deployment of the obtained results for different purposes. Big data computing amalgamates, as underpinning technologies, large-scale computation, new data-intensive techniques and algorithms, and advanced mathematical models to build and perform data analytics. Accordingly, big data computing demands a huge storage and computing power for data curation and processing for the purpose of discovering new or extracting useful knowledge typically intended for immediate use in an array of multitudinous decision-making processes to achieve different purposes. It entails the following components (see [12] for a detailed descriptive account):

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

The term 'big data' is essentially used to mean collections of datasets whose volume, velocity, variety, exhaustivity, relationality, and flexibility make it so difficult to manage, process, and analyze the data using the traditional database systems and software techniques. The term 'big data analytics' denotes 'any vast amount of data that has the potential to be collected, stored, retrieved, integrated, selected, preprocessed, transformed, analyzed, and interpreted for discovering new or extracting useful knowledge. Prior to this, the analytical outcome (the obtained results) can be evaluated and visualised in an understandable format before their deployment for decision-making purposes (e.g., improving, adjusting, or changing an operation, function, service, strategy, or policy)… In the domain of smart sustainable urbanism, big data analytics refers to a collection of sophisticated and dedicated software applications and database management systems run by machines with very high processing power, which can turn a large amount of urban data into useful knowledge for enhanced decision-making and deep insights in relation to various urban domains, such as transport, mobility, traffic, environment, energy, land use, waste management, education, healthcare, public safety, planning and design, and governance' [9], p. 234).

A survey of related work

In one of the earlier works on data-driven urbanism, Batty [5] describes how the growth of big data is shifting the emphasis from longer term strategic planning to short-term thinking about how cities function and can be managed. His argument revolves around the sea change in the kinds of data that are emerging about what happens where and when in cities, and how it is drastically altering the way we conceive of, understand, and plan smart cities. Bettencourt [7] explores how big data can be useful in urban planning by formalizing the planning process as a general computational problem. The focus in his paper is on scientific (complexity science) and engineering principles (big data technologies) pertaining to data-driven urbanism, and how they particularly relate to urban policy, management, and planning as to achieving new solutions to wicked and intractable urban problems. In his article 'The Real-time City? Big Data and Smart Urbanism' Kitchin [33] focuses on smart cities as increasingly composed of and monitored by pervasive and ubiquitous computing, and drawing on a number of examples, details how cities as being instrumented with digital devices and infrastructure produce big data which enable real-time analysis of city life, new modes of urban governance, and provide the raw material for envisioning and enacting more efficient, competitive, productive, open, and transparent cities. He moreover provides a critical reflection on the implications of big data and smart urbanism, examining five emerging concerns: the politics of big urban data; technocratic governance and city development; corporatization of city governance and technological lock-ins; buggy, brittle and hack-able cities; and the panoptic city. A large part of this examination is also the aim of Kitchin [34] paper, which indeed provides a critical overview of data-driven, networked urbanism and smart cities focusing in particular on the relationship between data and the city (rather than network infrastructure or computational or urban issues), and critically examines a number of urban data issues, including corporatization, ownership, control, privacy and security, anticipatory governance, and technical challenges. Kitchin [36] examines the forms, practices, and ethics of smart cities and urban science, paying particular attention to:

instrumental rationality and realist epistemology; privacy, dataveillance and geosurveillance; and data uses, such as social sorting and anticipatory governance. Overall, the above works lack an important strand to the topic of smart or data-driven urbanism: sustainability, and also tend to focus on either technical or political issues related to urban big data. In view of that, Bibri [11] provides a comprehensive, state-of-the-art review and synthesis addressing the sustainability and unsustainability of smart urbanism and related big data applications in terms of research issues and debates, knowledge gaps, technological advancements, as well as challenges and common open issues.

Research on big data analytics and its application in the context of smart cities tends to deal largely with economic development (i.e., management, efficiency, effectiveness, innovation, productivity, etc.), the quality of life in terms of service delivery betterment, and governance (e.g., [5, 11, 14, 12, 26, 31–34, 49] while overlooking and barely exploring the rather more urgent issues and complex challenges related to sustainability [8]. This paucity of research pertains particularly to the untapped potential of big data technologies and their novel applications for enhancing the environmental and social aspects of sustainability in the context of smart sustainable cities [8, 11, 12]. Indeed, many of the emerging smart solutions are not aligned with sustainability goals [1]. This relates to the deficiencies and misunderstandings of smart cities in this regard [11], to reiterate. Consequently, a recent research wave has started to focus on enhancing smart city approaches to achieve the required level of sustainability using big data applications under what is labelled 'smart sustainable cities' or 'sustainable smart cities' (e.g., [3, 6, 8, 11, 12]. Therefore, there are only a few studies that have recently focused on the uses of big data applications in relation to the different aspects of sustainability in the context of smart sustainable cities (see, e.g., [8, 9], Bibri [12, 15]. This lack of research can be explained by the fact that such cities are a new urban phenomenon, and the concept only became widespread during the mid 2010s.

Method: thematic analysis

It is assumed that in data-driven smart sustainable cities, there are concepts and applications that repeat themselves and compose distinct models of such cities in the context of sustainability. Therefore, this paper uses a qualitative approach to identify these concepts and applications as well as the underlying technologies, and eventually to identify the constructs behind them. This relates to the thematic analysis approach, where the aim of qualitative studies is to describe and explain a pattern of relationships, a process that entails a set of conceptual and subject categories [46] pertaining in this context to the data-driven smart sustainable city.

Following a set of qualitative 'tactics' suggested by Miles and Huberman [45] that can assist in generating meanings from diverse material, a thematic analysis was designed and employed with two purposes in mind. First, to identify the most advanced big data applications related to the three dimensions of sustainability and related concepts and technologies. Second, to conceptualize the theoretical base behind the model of the data-driven smart sustainable city with the underlying technological and other components. As an inductive analytic approach, thematic analysis can be used to address the different types of questions posed by researchers to produce complex conceptual or analytical cross-examinations of meaning in qualitative material. This can be done through discovering patterns, relationships, themes, and concepts in this material that include multidisciplinary and interdisciplinary literature. Thereby, thematic analysis is an appropriate approach when analyzing and synthesizing a large body of documents—in the form of, for example, conceptual frameworks and descriptive accounts. It can be applied to produce theory-driven analyses.

The main steps of this study's thematic analysis approach are as follows:

1. Review of smart cities, sustainable cities, data-driven cities, big data technologies and their novel applications, and other multidisciplinary and interdisciplinary literature. The aim is to deconstruct a multidisciplinary and interdisciplinary text related to the model of the data-driven smart sustainable city that puts emphasis on instrumentation, datafication, and computerization and related big data applications for multiple urban systems and domains. The outcome of this process entails numerous themes, applications, technologies, and urban centers, that are related to the respective model.
2. Pattern recognition entails the ability to see patterns in seemingly random information. The purpose is to note major patterns and concepts within the result of the first step, and then to, in this second step, look for similarities or patterns and organize the results by concepts.
3. Identifying a city model involves recognizing a specific and distinctive model of the data-driven smart sustainable city.
4. Conceptualization is about finding theoretical relationships among the identified concepts and the data-driven smart sustainable city.

Results and discussion

As cities are routinely embedded with all kinds of ICT forms, including infrastructure, platforms, systems, devices, sensors and actuators, and networks, the volume of data generated about them is growing exponentially and diversifying, providing rich, heterogenous streams of information about urban environments and citizens. This data deluge enables the real-time analysis of different urban systems and interconnects data across different urban domains to provide detailed views of the relationships between different forms of data that can be utilized for advancing the various aspects of urbanity through new modes of operational functioning, planning, design, development, and governance in the context of sustainability, as well as provides the raw material for envisioning more sustainable, efficient, resilient, and livable cities. The point at issue is that we generate enormous amounts of data on a daily basis, a binary trail of breadcrumbs that forms a map of urban life in terms of citizens' experiences and urban dynamics, and these disparate datasets, if harnessed properly, open up a unique window of, and represent a goldmine, opportunity for making cities more sustainable and in tune with citizens' actual needs and aspirations.

On the evolving integration of data-driven smart cities and sustainable cities

Both smart cities and sustainable cities are becoming ever more computationally augmented and digitally instrumented and networked, their systems interlinked and integrated, their domains combined and coordinated, and thus their networks coupled and interconnected, and consequently, vast troves of urban data are being generated and used to control, manage, organize, and regulate urban life in real time [11, 12]. In other words, the increasing pervasiveness of urban systems, domains, and networks utilizing digital technologies is generating enormous amounts of digital traces capable of reflecting in real time how people make use of urban spaces and infrastructures and how urban activities and processes are performed, an information asset which is being leveraged in steering smart cities and sustainable cities. Indeed, citizens leave their digital traces just about everywhere they go, both voluntarily and involuntarily, and when cross-referenced with each citizen's spatial, temporal, and geographical contexts, the data harnessed at this scale offers a means of describing, and responding to, the dynamics of the city in real time. In addition to individual citizens, city systems, domains, and networks constitute a key source of data deluge, which is generated by various urban entities, including governmental agencies, authorities, administrators, institutions, organizations, enterprises, and communities by means of urban operations, functions, services, designs, strategies, and policies.

Smart cities are increasingly connecting the ICT infrastructure, the physical infrastructure, the social infrastructure, and the economic infrastructure to leverage their collective intelligence, thereby striving to render themselves more sustainable, efficient, functional, resilient, livable, and equitable. It follows that smart cities of the future seek to solve a fundamental conundrum of cities—ensure sustainable socio-economic development, equity, and enhanced quality-of-life at the same time as reducing costs and increasing resource efficiency and environment and infrastructure resilience. This is increasingly enabled by utilizing a fast-flowing torrent of urban data and the rapidly evolving data analytics technologies; algorithmic planning and governance; and responsive, networked urban systems. In particular, the generation of colossal amounts of data and the development of sophisticated data analytics for understanding, monitoring, probing, regulating, and planning the city is one significant aspect of smart cities that is being embraced by sustainable cities to improve, advance, and maintain their contribution to the goals of sustainable development (see, e.g., [8, 9, 12, 15, 17]. Generally, a sustainable city can be understood as a set of approaches into operationalizing sustainable development in, or practically applying the knowledge about sustainability and related technologies to the planning and design of, existing and new cities or districts. It represents an instance of sustainable urban development, a strategic approach to achieving the long-term goals of urban sustainability. Accordingly, it needs to balance between the environmental, social, and economic goals of sustainability as an integrated process. Specifically, as put succinctly by Bibri and Krogstie ([14], p. 11), a sustainable city 'strives to maximize the efficiency of energy and material use, create a zero-waste system, support renewable energy production and consumption, promote carbon-neutrality and reduce pollution, decrease transport needs and encourage walking and cycling, provide efficient and sustainable transport, preserve ecosystems and green space, emphasize design scalability and spatial proximity, and promote livability and community-oriented human environments.'

There are different instances of sustainable cities as an umbrella concept, which are identified as models of sustainable urban forms. Of these, the compact city and the eco–city are advocated as more sustainable and environmentally sound models [12]. From a conceptual perspective, Jabareen [28] ranks the compact city as more sustainable than the eco–city. Ideally, the compact city secures socially beneficial, economically viable, and environmentally sound development through dense and mixed use patterns that rely on sustainable transportation [18, 22, 29, 30]. It emphasizes, in addition to density, mixed-land uses, and sustainable transportation, compactness, social mix or diversity, high standards of environmental and urban management systems, energy–efficient buildings, closeness to local squares, more space for bikes and pedestrians, and green areas [12]. Whereas the eco–city focuses on renewable resources, passive solar design, ecological and cultural diversity, urban greening, and environmental management and other environmentally sound policies [28]. The eco–city encompasses a wide range of urban–ecological proposals that seek to achieve urban sustainability within different local and national contexts (see [48] for a set of case studies). These approaches propose a wide range of environmental, social, and institutional policies that are directed to managing urban spaces to achieve sustainability, and this type emphasizes environmental management and promotes the ecological agenda through a set of institutional and policy tools [28]. All in all, the effects of the compact city and the eco-city combined are compatible with the fundamental goals of sustainable development.

Furthermore, for supra-national states, national governments, and city officials, smart cities offer the enticing potential of environmental and socio-economic development—more sustainable, livable, functional, safe, equitable, and transparent cities, and the renewal of urban centers as hubs of innovation and research (e.g., [3, 6, 11, 12, 33, 41, 52]. While there are several main characteristics of a smart city as evidenced by industry and government literature (see, e.g., [27, 33] for an overview), the one that this paper is concerned with focuses on environmental and social sustainability.

There has recently been much enthusiasm in the domain of smart sustainable urbanism about the immense possibilities and fascinating opportunities created by the data deluge and its extensive sources with regard to enhancing and optimizing urban operational functioning, management, planning, design, and governance in line with the goals of sustainable development as a result of thinking about and understanding sustainability and urbanization and their relationships in a data-analytic fashion for the purpose of generating and applying knowledge-driven, fact-based, strategic decisions in relation to such urban domains as transport, traffic, mobility, energy, environment, education, healthcare, public safety, public services, governance, and science and innovation [12].

Therefore, the operational functioning, management, planning, and design of smart sustainable cities as a set of interrelated systems is increasingly being dominated by the use of advanced data, information, and communication technologies. The provision of data from urban operations and functions is offering the prospect of urban environments wherein the implication of the way such cities are functioning and operating is continuously available, and urban planning is facing the prospect of becoming continuous as the data deluge floods from different urban domains and is updated in real time, thereby allowing for a dynamic conception of planning and a scalable and efficient form of design [12].

Digital instrumentation

The big data revolution is set to erupt in both smart cities and sustainable cities throughout the world. This is manifested in bits meeting bricks on a vast scale as instrumentation is routinely pervading the spaces we live in. Smart sustainable cities are depicted as constellations of instruments for measurement and control across many spatial scales that are connected through fixed and wirelessly ad hoc and mobile networks with a modicum of intelligence, which provide and coordinate continuous data regarding different aspects of urbanity in terms of the flow of decisions about the physical, infrastructural, operational, functional, and socio-economic forms of smart sustainable cities [8]. As such, the instrumentation of such cities offers the prospect of an objectively measured, real-time analysis of urban life and infrastructure, and opens up dramatically different forms of social organisation. It is the domain of the ICT industry that is providing the detailed hardware and software to provide the operating system for smart sustainable cities. This infrastructure entails integration, data collection and mining, decision making, practice enhancement, and service delivery in relation to sustainability, efficiency, resilience, equity, and the quality of life.

While there are different approaches to generating the deluge of urban data (e.g., directed, indirected, volunteered, etc.), the automated one is the most common and prominent among them. It pertains to various automatic functions of the devices and systems that are widely deployed and networked across urban environments. Indeed, the automated approach to urban data deluge generation has recently captured the imagination of those concerned with understanding, operating, managing, and planning cities, as well as seeking useful insights into urban systems, in particular in relation to the environment [9]. Especially, there has been increased interest in sensor networks and the IoT as well as the tracking and tracing of people and objects [33]. For example, sensors networks can be used to monitor the operation and condition of urban and public infrastructures, such as roads, rails, tunnels, sewage systems, water systems, power and gas provision systems, hospitals, facilities, and parks, as well as environmental conditions. In this context, smart sustainable/sustainable smart cities offer the prospect of real-time analysis of the processes operating and organizing urban life, which is of paramount importance to advancing the different aspects of sustainability. There are a number of tools and techniques used in the automated approach to generating urban data deluge (e [6, 9, 12, 23, 33, 39], including sensors:

- Global Positioning System (GPS) in vehicles and on people.
- Smart tickets that are used to trace passenger travel.
- RFID tags attached to objects and people.
- Sensed data generated by a variety of sensors and actuators embedded into the objects or environments that regularly communicate their measurements.
- Capture systems in which the means of performing tasks captures data about those tasks.
- Digital devices that record and communicate the history of their own use.

- Digital traces left through purchase of goods and related demand supply situations.
- Transactions and interactions across digital networks that not only transfer information, but also generate data about the transactions and interactions themselves.
- Clickstream data that record how people navigate through websites or apps.
- Automatic Meter Reading (AMR) that communicates utility usage on a continuous basis.
- Automated monitoring of public services provision.
- The scanning of machine-readable objects such as travel passes, passports, or barcodes on parcels that register payment and movement through a system.
- Machine to machine interactions across the IoT.
- Uniquely indexical objects and machines that conduct automatic work as part of the IoT, communicating about their use and traceability if they are mobile (automatic doors, lighting and heating systems, washing machines, security alarms, wifi router boxes, etc.)
- Transponders that monitor throughput at toll-booths, measuring vehicle flow along a road or the number of empty spaces in a car park, and track the progress of buses and trains along a route.

In view of the above, embedding more and more advanced ICT in various forms into smart sustainable/sustainable smart cities will undoubtedly continue and even escalate for the purpose of providing the most suitable tools and methods for handling the underlying complexity and thus dealing with the challenges they are facing and will continue to face. Especially, advanced ICT has an instrumental and shaping role in not only monitoring, understanding, and analyzing such cities, but also in improving sustainability, efficiency, resilience, and the quality of life in them. With that in regard, the broad availability of urban data is pushing research ever more into further advancing the core enabling technologies of big data analytics towards realizing and implementing urban intelligence functions and related simulation models and optimization and prediction methods.

From a different perspective, not all data are equally generated, and their variety is associated with the purpose of their use, among others. There are opportunistic data which are collected for one purpose and then used for another, e.g., data owned by cellphone companies to run their operations but used by transport companies to better understand urban mobility. User-generated data result from the engagement of citizens, e.g., data from social media platforms which provide valuable information to better understand today's cities. Purposely sensed data, e.g., automated data, reflect the power of ubiquitous urban sensors that can be deployed ad hoc in public and private spaces to better understand some aspects of urban life and dynamics.

Moreover, the various sensor recording parameters, their length as to the collected data, where they are located, what kinds of sensors are embedded in which environments, their settings and calibration, their integration and fusion, and their exhaustiveness as technical configurations and deployments determine the nature of the produced data and the way they are stored, managed, processed, analyzed, and disciplined [12].

Big data ecosystem and its components

Big data trends are associated with pervasive and ubiquitous computing, which involves myriads of sensors pervading urban environments on a massive scale. Therefore, the volume of the data generated is huge and thus the processes, systems, platforms, infrastructures, and networks involved in handling these data are complex. Mechanisms to store, integrate, manage, process, analyze, and visualize the generated data through scalable applications remain a major scientific and technological challenge in the ambit of data science, urban science, and computer science.

The evolving data deluge is due to a number of the core enabling and driving technologies of ICT of pervasive and ubiquitous computing and thus big data computing. These are being fast embedded into the very fabric of contemporary cities, everyday practices and spaces, whether badging or regenerating themselves as smart sustainable to pave the way for adopting the upcoming innovative solutions to overcome the challenges of sustainability and urbanization in the years ahead. Further, like many areas to which big data computing can be applied, smart sustainable cities require the big data ecosystem and its components to be put in place as part of their ICT infrastructure prior to designing, developing, deploying, implementing, and maintaining the diverse applications that support sustainability and reduce the negative effects of urbanization. As a scientific and technological area, the core enabling technological components underlying the big data ecosystem are under vigorous investigation in both academic circles as well as the ICT industry towards the development of computationally augmented urban environments as part of the informational landscape of such cities [11]. Big data ecosystems are for capturing data to generate useful knowledge and deep insights. In the sphere of smart sustainable cities, the big data landscape is daunting, and there is no one 'big data ecosystem' or single go-to solution when it comes to building big data architecture. The big data ecosystem involves multivarious technologies in terms of quality and form, which allow to store, manage, process, analyze, visualize data, and deploy the obtained results. It consists of infrastructure and tools for storing, managing, processing, and analyzing data; specialized analytics techniques; and applications. Bibri and Krogstie [16] provide a comprehensive, state-of-the-art review of the core enabling technologies of big data analytics in relation to smart sustainable cities, including a synthesis and illustration of the key computational and analytical techniques, processes, and models associated with the functioning and application of big data analytics. The components addressed by the authors in rather more detail include, but are not limited to, the following:

- Pervasive sensing in terms of collecting and measuring urban big data; the IoT and related RFID tags; sensor-based urban reality mining; and sensor technologies, types, and areas in big data computing.
- Wireless communication network technologies and smart network infrastructures.
- Data processing platforms.
- Cloud and fog/edge computing.
- Advanced techniques and algorithms.
- Conceptual and analytical frameworks.

Generally, big data ecosystems entail a number of permutations of the underlying core enabling technologies as shaped by the scale, complexity, and extension of the city projects and initiatives to be developed and implemented. In this respect, it is necessary to, as suggested by Chourabi et al. [20], take into account flexible design, quick deployment, extensible implementation, comprehensive interconnections, and advanced intelligence. Regardless, while there are some permutations that may well apply to most urban systems and domains, there are some technical aspects and details that remain specific to smart sustainable cities, more specifically to the requirements, objectives, and resources of related projects and initiatives, which are usually determined by and embedded in a given context [11, 16]. Yet, most of, if not all, the possible permutations involve sensing technologies and networks, data processing platforms, cloud computing and/or fog computing infrastructures, and wireless communication and networking technologies. These are intended to provide a full analytic system of big data and related functional applications based on advanced decision support systems and strategies—urban intelligence functions and related simulations models and optimization and prediction methods [12]. On this note, Batty et al. [6] state that much of the focus on sustainable smart cities of the future, 'will be in evolving new models of the city in its various sectors that pertain to new kinds of data and movements and actions that are largely operated over digital networks while at the same time, relating these to traditional movements and locational activity. Very clear conceptions of how these models might be used to inform planning at different scales and very different time periods are critical to this focus… Quite new forms of integrated and coordinated decision support systems will be forthcoming from research on smart cities of the future'.

Cloud computing for big data analytics

Characteristics and benefits

The term 'cloud computing' has been defined in multiple ways by ICT experts and researchers and a wide range of organizations (e.g. government agencies) and institutions (e.g., educational institutions). Common threads running through most definitions are that cloud computing denotes a computing model in which standardized, scalable, and flexible ICT-enabled capabilities delivered in real-time via the Internet in the form of three types of services: (1) Software-as-a-Service (SaaS), (2) Platform-as-a-Service (PaaS), and (3) Infrastructure-as-a-Service (IaaS) to external users or customers. SaaS and PaaS denote the provider's software applications and software development platforms respectively, and IaaS means virtual servers, storage facilities, processors, and networks as resources, all being delivered over the cloud. Thus, cloud computing consists of several components, which can be rapidly provisioned with minimal management effort. However, the diversity of the definitions of, coupled with the lack of agreement over what constitutes, cloud computing has created confusion as to what it really means as an emerging computing model, and consequently its definitions have been criticized for being too broad and unclear [12].

Having attracted attention and gained popularity worldwide, cloud computing is becoming increasingly a key part of the ICT infrastructure of both smart cities and sustainable cities as an extension of distributed and grid computing due to the prevalence of sensor technologies, storage facilities, pervasive computing infrastructures, and wireless communication networks. Especially, most of these technologies have become technically mature and financially affordable by cloud providers. By commoditizing services,

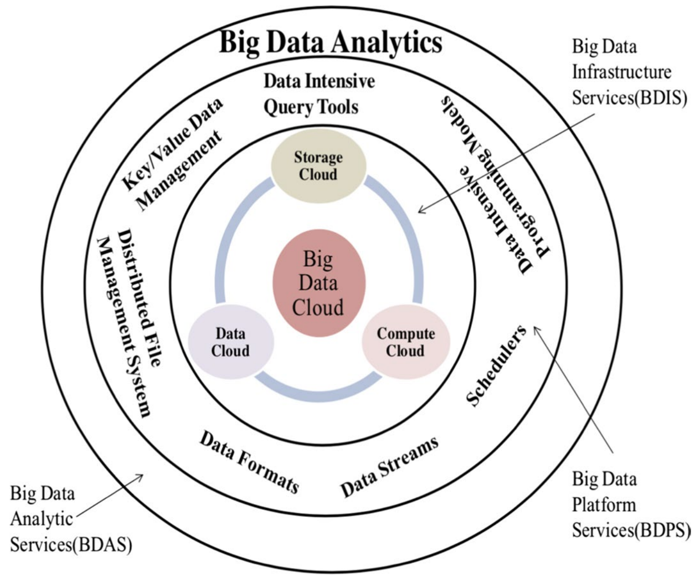

Fig. 1 Big data cloud components

low cost open source software, and geographic distribution, cloud computing is becoming increasingly an attractive option.

Users of cloud computing, including individuals, organizations, and government agencies employ it to, as a variety of enabled services, store and share information; manage, sift, and analyze databases; and deploy Web services, including processing huge datasets for complicated problems of scientific kinds [8]. Cloud computing can also be used to process urban big data and context data in relation to smart sustainable city applications.

Overall, among the key advantages provided by cloud computing technology include cost reduction, location and device independence, virtualization (sharing of servers and storage devices), multi-tenancy (sharing of costs across a large pool of cloud provider's clients), scalability, performance, reliability, and maintenance [8]. Therefore, opting for cloud computing to perform big data analytics in the realm of smart sustainable cities (see [12] for an illustrative example of the application of cloud computing) remains thus far the most suitable option for the operation of infrastructures, applications, and services whose functioning is contingent upon how urban domains interrelate and collaborate, how efficient they are, and to what extent they are scalable as to achieving and maintaining the required level of sustainability [8].

Elements of big data

Big data analytics can be performed in the Cloud. This involves both big data Platform as a Service (PaaS) and Infrastructure as a Service (IaaS). In line with the definition of cloud computing, there are three main elements of big data cloud (Fig. 1). Konugurthi et al. [42] describe them below:

1. Big Data Infrastructure Services (BDIS): This layer offers core services, such as compute, storage, and data services for big data computing, as described below:

- Basic storage service: Provides basis services for data delivery, which is organized either on physical or virtual infrastructure, and supports various operations, such as create, delete, modify, and update, with a unified data model supporting various types of data.
- Data organization and access service: Provides management and location of data resources for all kinds of data, as well as selection, query transformation, aggregation and representation of query results, and semantic querying for selecting the data of interest.
- Processing service: Mechanisms to access the data of interest, transferring to the compute node, efficient scheduling mechanism to process the data, programming methodologies, and various tools and techniques to handle the variety of data formats.

The elements of BDIS are described below:

- Computing Clouds: On demand provisioning of compute resources, which can expand or shrink based on the analytics requirements.
- Storage Clouds: Large volume of storages offered over the network, including file system, block storages, and object-based storage. Storage clouds offer to create file system of choice and also elastically scalable. They can be accessed based on the pricing models which are usually based on data volumes or data transfer. The several services provided in this regard are raw, block, and object-based storages.
- Data Clouds: Are similar to Storage Clouds but unlike storage space delivery. They offer data as a service. Data Clouds offer tools and techniques to publish the data, tag the data, discover the data, and process the data of interest. Data Clouds operate on domain specific data leveraging the Storage Clouds to serve data as a service based on the four step of thr Standard Scientific Model, such as data collection, analysis, analyzed reports, and long-term preservation of the data.

2. Big Data Platform Services (BDPS): This layer offers schedulers, query mechanisms for data retrieval, and data-intensive programming models to address several big data analytic problems.

3. Big Data Analytics Services (BDAS): Big data analytics as services over big data-cloud infrastructure.

Urban operating centers and strategic planning and policy offices

The consequence of the evolving and soaring data deluge is that data-driven urbanism is changing how we know, operate, regulate, manage, plan, and govern city systems, both within particular domains and across them (e.g., [6, 8, 9, 11, 12, 36, 38, 44, 52]. Indeed, one of the implications of such urbanism is that urban systems are becoming much more tightly interlinked and integrated and urban domains highly coordinated, especially in the context of sustainability [12]. New data streams from such domains are changing how to use data science to extract and analyze these data to make a real impact.

There has recently been a marked tendency supported by practical endeavors to draw all the kinds of analytics associated with the city in terms of its urban domains into a single hub, supported by broader public and open data analytics. This entails creating a city-wide instrumented or centralized system that draws together data streams from many agencies (across city domains) for large scale analytics. For example, urban operating systems explicitly link together multiple urban technologies to enable greater coordination of urban systems and domains [36], especially for the purpose of advancing sustainability [9]. Similarly, urban operating centers attempt to draw together and interlink urban big data to provide integrated and holistic views and synoptic city intelligence [36, 38] through processing, analyzing, visualizing, and monitoring the vast deluge of urban data that is used for real-time decision-making using advanced data analytics techniques. A notable example is the Centro De Operacoes Prefeitura Do Rio, an urban operations center staffed by 400 professional works for monitoring the operational functioning of the city [36]. Here, the aim is to knock down silos between different urban departments and to combine each one's data to help the whole enterprise [51] as a complex endeavor. Indeed, this urban operations center draws together real-time data streams from 30 agencies, including public transport and traffic, mobility, power grid, municipal and utility services, emergency services, weather feeds, information sent in by the public via smartphones, and social media networks into a single data analytics center [33, 36]. Urban operations centers provide a powerful means for making sense of, managing, and living in the city in the here-and-now, as well as for planning the city in terms of envisioning and predicting future scenarios, which is of value for those developing and using integrated, real-time city data analytics [33]. Examples of city operating systems or control rooms include Microsoft's *CityNext,* Urbiotica's *City Operating System,* IBM's *Smarter City,* and PlanIT's *Urban Operating System,* with the latter representing Enterprise Resource Planning (ERP) systems as intended to operate and coordinate the activities of large companies repurposed for cities [34].

There has been a transformation in the attributes of the data being collected, stored, and organized in datasets, This transformation has been enabled by new networked, digital technologies embedded into the fabric of urban environments that underpin the drive to create smart sustainable cities. In this context, many different initiatives in collecting data from new varieties of digital access are being fashioned, such as the satellite-enabled GPS in vehicles and on citizens, from social media sites, from transactions, and from access to numerous kinds of web sites. Satellite remote-sensing is increasingly widely deployed, in addition to a variety of scanning technologies associated with the IoT [9]. Other technologies include digital cameras, sensors, transponders, meters, actuators, and transduction loops that monitor various phenomena and continually send data to an array of control and management systems, such as urban operations centers, centralized control rooms, intelligent transport systems, logistics management systems, energy grids, and building management systems that can process and respond in real time to the data flow [25, 33, 36].

For example, data on traffic flow generated by sensors, cameras, transponders, and transduction loops in public transport systems can be produced in a real-time manner, fed back to a control room where analysts can monitor traffic levels using advanced software applications and alter traffic light sequencing and road speeds to try and maintain traffic flow [36]. This relates to smart traffic lights and signals (see

[9] for a descriptive account). The big data application for traffic also involves the possibility of determining travel patterns across times of the day and days of the week concerning all nodes on the network, such as bus stops, sensor locations, and junctions, as well as creating and improving models and simulations to guide future urban development (e.g., to simulate what might happen to travel patterns by closing a road on the network). For a detailed account of diverse big data applications for environmental sustainability in the context of smart sustainable cities, including, in addition to traffic, mobility, energy, power grid, environment, buildings, infrastructure, and large scale deployment, the reader can be directed to Bibri [9].

In addition, the Policy and Strategic Planning Office in New York City has sought to create a data analytic hub to weave together data from a diverse set of city agencies in order to try to manage, regulate, plan, and govern the city more efficiently and effectively [33]. Huge amounts of data amounting to petabytes stream through the office on a daily basis for analysis in terms of cross-referencing data, spotting patterns and identifying and solving city problems [24, 33]. A more ambitious endeavor in this direction would be to realize a joined-up planning, which entails an integration that enables systemwide effects to be understood, analyzed, tracked, and built into the very designs and responses that characterize the operations, functions, and services of the city. This involves connection, networks, and data integration in regard to urban agencies or domains.

A team of data analysts and other data operatives, aided by various data analytics software, monitor, manage, process, analyze, and visualize the vast deluge of urban data, alongside data aggregated over time and huge volumes of other kinds of data in terms of velocity, i.e., released on a more periodic basis, often mashing the datasets together to investigate particular aspects of city life and changes over time, and to build predictive models with respect to city management, planning, design, and development in the context of sustainability. The outcome is to be used for real-time decision-making and problem solving pertaining to urban operations and functions, as well as to other urban practices. In this respect, the data-driven city enables to make decisions by assessing what is happening at any one time and by responding and planning appropriately with respect to sustainability. Such assessment entails interlinking diverse forms of data, which provides a deeper, more holistic and robust analysis. This therefore allows for developing, running, regulating, and planning the city on the basis of strong, rationale evidence.

The implication and prospect of the above endeavors is a new form of highly responsive urbanism in which big data technologies and their systems are prefiguring and setting the urban agenda for sustainable development and influencing and controlling how city systems respond to and perform as to the goals of sustainable development.

Living labs

Smart sustainable cities revolves around the idea of a living laboratory for new technologies that can handle all the major systems a city requires and the key domains it involves. There are several descriptions and definitions of a living lab, according to different sources (e.g., [43, 47, 50]. In the context of this paper, a living lab as a research concept (e.g., [2, 19, 56] refers to a user-centered, open-innovation ecosystem operating in the city and targeted at improving sustainability through data-driven smart solutions and approaches, integrating innovation processes and concurrent research within a partnership involving public and private organizations and institutions, as well as citizens and communities. As such, it brings together interdisciplinary and transdisciplinary scholars, researchers, experts, and practitioners to develop, deploy, implement, and test in actual urban environments new technologies and strategies for design that respond to the long-term goals of sustainability. The endeavor here spans in city scale from the physical to the social and ecological, and addresses challenges related to the built environment in the context of sustainable urban forms. Especially, the effects of such forms are compatible with the goals of sustainable development in terms of transport provision, mobility and accessibility, travel behavior, energy conservation and efficiency, pollution and waste reduction, public health and safety, economic viability, and life quality [12]. In addition, in terms of the living lab process, the act of co-creating, exploring, experimenting, testing, and discovering—all of breakthrough scenarios, visions, ideas, concepts, and related technological artefacts in real-life setting in terms of urban design and services can generate scientific and practical innovations of high potential for advancing sustainability. This approach allows all the involved city stakeholders to concurrently consider both the global performance of data-driven smart sustainability solutions and their potential adoption by cities on different spatial scales. In all, the concept of the living lab this paper is concerned with relates to planners, scholars, researchers, scientists, experts, policymakers, and citizens for co-designing, exploring, experiencing, and refining new urban functions, services, strategies, policies, and regulations in real-life scenarios for evaluating their potential impacts on sustainability before their implementations.

Today, new technologies are giving citizens more opportunities to participate in the functioning, design, and governance of the city, which is being increasingly leveraged in the transition towards the needed sustainable development. Changes driven by digital technologies can happen without heavy infrastructure, as they can arise from bottom-up actions instead of being necessarily determined by city governments. These should therefore develop knowledge sharing platforms that get citizens engaged as much as possible and excited about smart sustainable urban transformations through open innovation and participatory research. Indeed, citizens can really be the ones to bring such transformations, if the right platforms can be created, and the installation and control of hardware can be done for no more than what citizens wish their city to become and how they aspire to see it evolving in the future.

An example of a living lab is the multipurpose experimental facility built by Zero Emission Buildings (ZEB), Faculty of Architecture and Fine Arts, the Norwegian University of Science and Technology (NTNU). As a test facility occupied by real persons using the building as their home, it focuses on the occupants and their use of innovative building technologies. This living laboratory is used to study various technologies and design strategies in a real-world living environment:

- User-centerd development of new and innovative solutions: The test facility is used within a comprehensive design process focusing on user needs and experiences.
- Performance testing of new and existing solutions: Exploring building performance in a context of realistic usage scenarios.

- Detailed monitoring of the physical behaviour of the building and its installations as well as the users influence on them.

ZEB researchers within the fields of architecture, social science, materials science, building technologies, energy technologies, and indoor climate jointly study the interaction between the physical environment and the users.

This living lab and other similar initiatives related to different areas of sustainability are at the core smart sustainable cities in terms of their specific structural components. Examples of such initiatives relate to the design concepts and typologies characterizing the compact city and the eco-city as combined landscapes and approaches, notably compactness, density, mixed-land use, diversity, sustainable transport, passive solar design, and ecological design. Specifically, the multipurpose experimental facilities the proposed model is concerned with will focus on the significant themes evident in the current debates on various strategies and their effects and benefits in the context of sustainable urban forms. See Bibri [8] for a detailed list of these themes and strategies.

Innovations labs

Exploring the notion of smart sustainable cities as an innovation lab is about evolving urban intelligence functions associated with optimizing and enhancing operations, functions, services, designs, strategies, and policies across various urban domains in line with the goals of sustainable development. This can take the form of laboratories. Especially, building models of cities functioning in real time from routinely sensed data is becoming increasingly achievable and deployable (e.g., [6, 12, 33]. Although innovation labs are springing up everywhere, becoming now commonplace across industries, most of such initiatives still relate to the business domain.

In the context of this paper, an innovation lab denotes a working space designed to optimize and enhance sustainability innovation in the form of urban intelligence functions. It is a unique environment devoted to or exclusively intended for sharing and building new and expert knowledge, creating new ideas and alignment, and developing comprehensive solutions for sustainability in response to the needs, aspirations, and goals of the city and its stakeholders and citizens. An innovation lab also serves as an environment where a team of researchers, scientists, practitioners, and professionals can gather and design thinking for innovation can directly happen in relation to sustainability solutions, meaning it is designed to host innovation workshops. The key strengths lie in the team's multidisciplinary knowledge and skills, long-standing experience, international know-how, and access to global networks in the sphere of urban sustainability and related technologies. Further, among the questions that an innovation lab for urban sustainability involve transport and traffic, mobility, energy, power grid, environment, buildings, infrastructures, design and planning, scientific research, governance, healthcare, public safety, and big data technology. This implies that such lab should host many interdisciplinary and transdisciplinary teams concerned with different city domains or sub-domains and the associated solutions. Applicable solutions for various areas of sustainability should be developed considering the interests of city stakeholders as well as citizens. The positioning of such lab should make it possible to offer a platform where the many, scientifically excellent research initiatives of the city in these areas can cooperate even more strongly with each other. The idea is to make a scientific contribution to the social discourse of the data-driven smart sustainable city within the framework of the innovation lab for urban sustainability. One way to support innovation within smart sustainable cities involves a set of strategic and goal-focused units, focused on specific areas that link big data technology to sustainability, tasked with creating anything from a new solution to a new method, model, or technology. Another innovation initiative, which may not be physically co-located, can involve setting up a group to collaborate with industry and academia.

Setting up an innovation lab involves significant challenges, which pertain to the many questions that the smart sustainable city stakeholders need to ask themselves in the course of creating an innovation lab for sustainability. These questions involve what roles should be filled, what types and combinations of people make the best innovators, what governance model or framework should be applied, which projects should be prioritized, how to establish synergies with the rest of city projects, what kind of infrastructure should be in place, how can ideas and models be tested, and so on.

ICT is being developed to increase the efficiency of energy systems and the delivery of public and social services, to improve transportation and mobility, and to enhance the quality of life, among others. This reflects the notion of the smart sustainable city as a laboratory for innovation or research center. For example, the Research Center on Zero Emission Neighbourhoods in Smart Cities at NTNU, which was established in 2017 by the Research Council of Norway, is a research center for environmentally friendly energy. More specifically, it conducts research on zero emission neighbourhoods in smart cities. Its goal is to develop solutions for future buildings and neighbourhoods with no greenhouse gas (GHG) emissions and thereby contribute to a low carbon society. Its main objective is to develop products and processes that will lead to the realization of sustainable neighbourhoods as to their production, operation, and transformation. In line with the goals of smart sustainable cities, the ZEN research is driven by the vision and convinced that future communities and cities should ensure optimal energy use and be good places for people to live and work in. The main question the ZEN research center is concerned with—which indeed is at the core of how sustainable urban forms should be monitored, understood, and analyzed to improve, advance, and maintain their contribution to the goals of sustainable development—is how the sustainable neighbourhoods of the future should be designed, built, transformed, and managed to reduce their GHG emissions towards zero.

As with most of innovation centers, the idea of the ZEN research center is to bring together like minded people to share ideas and create the future. The partners of this center cover the entire value chain and include representatives from municipal and regional governments, property owners, developers, consultants and architects, ICT companies, contractors, energy companies, manufacturers of materials and products, and governmental organizations. NTNU is the Center's host and leads it together with SINTEF Building and Infrastructure and SINTEF Energy. In order for the ZEN research center to achieve its high ambitions, the process of strategizing and planning is done together with these partners to:

- Develop neighborhood design and planning instruments while integrating science-based knowledge on GHG emissions.
- Create new business models, roles, and services that address the lack of flexibility towards markets and catalyze the development of innovations for a broader public use.
- Create cost effective and resource and energy efficient buildings by developing low carbon technologies and construction systems based on lifecycle design strategies.
- Develop technologies and solutions for the design and operation of energy flexible neighborhoods.
- Develop a decision-support tool for optimizing local energy systems and their interaction with the larger system.
- Create and manage a series of neighbourhood-scale living labs, which will act as innovation hubs and a testing ground for the solutions developed in the ZEN Research Center.

Similar to ZEB, this research center and other similar initiatives related to different areas of sustainability are at the core of smart sustainable cities in terms of their specific components. Examples of such initiatives relate to the design concepts and typologies characterizing the compact city and the eco-city as combined landscapes and approaches, notably compactness, density, mixed-land use, diversity, sustainable transport, passive solar design, and ecological design. Specifically, the research centers the proposed model is concerned with will focus on the significant themes evident in the current debates on various strategies and their effects and benefits in the context of sustainable urban forms. For example, cleaner modes of transportation-such as bike-sharing systems is a potential area for research and innovation based on mapping how and when people travel so as to know where to invest in such modes, and hence mobilize and align stakeholders.

Urban intelligence functions

In the context of this paper, the concept of urban intelligence refers to the planning, development, integration, and deployment of big data computing and underpinning technologies as an ecosystem (both physical and virtual assets) to support the interoperability between resources and technologies and hence the integration of urban systems and the coordination of urban domains to serve the city and its stakeholders and citizens with respect to sustainability dimensions. In short, urban intelligence entails the use of big data analytics and the underlying core enabling technologies to address and overcome the problems and challenges facing cities in the context of sustainability.

As an advanced form of decision support, urban intelligence functions integrate, synthesize, and analyze data flows for the purpose of improving the sustainability, efficiency, resilience, equity, and quality of life in cities. This relates in this context to exploring the notion of smart sustainable cities as innovation labs. Accordingly, the kind of urban intelligence functions that such city should evolve in the form of laboratories that enable its monitoring, planning, design, and development include, but are not limited to, the following:

- The efficiency of energy systems.
- The improvement of transportation and communication systems.
- The improvement of water, power, and sewage systems.
- The enhancement of urban metabolism.
- The effectiveness of distribution systems.
- The robustness and resilience of urban infrastructures in terms of their ability to withstand adverse conditions and to quickly recover from difficulties.
- The efficiency and scalability of urban design in terms of forms, structures, and spatial organizations.
- The optimal use and accessibility of facilities.
- The efficiency of social and public services delivery.
- The optimization of ecosystem services provision.
- The dynamic, continuous, and short-term forms of planning.

Urban intelligence functions represent new conceptions of how smart sustainable cities function and utilize and combine complexity science and urban science in fashioning new powerful forms of urban simulations models and optimization and prediction methods that can generate urban structures and forms as well as spatial organizations and scale stabilizations that improve sustainability, efficiency, resilience, equity, and the quality of life [12]. They are best to take the form of laboratories for scientific and social research and innovation directed primarily for improving, advancing, and maintaining the contribution of such cities to sustainability. Urban intelligence labs are intended to work directly with various urban entities (e.g., government agencies, public authorities, organizations, institutions, companies, communities, citizens, etc.) to acquire, process, and analyze data and then derive useful knowledge and insight in the form of applied intelligence. Their core aim is to solve tangible and significant problems of city planning and design through data-driven decision-making. This involves delivering problem-oriented research that serves the dual purpose of advancing the scientific understanding of cities in terms of sustainability and urbanization and how they intertwine with and affect one another, as well as in terms of having a direct impact on decision-making and action taking in the sense of enhancing and advancing planning practices. In this light, the sort of intelligence functions envisaged for smart sustainable cities would be woven into the fabric of institutions whose mandate is to promote, improve, and advance sustainability and create a better quality of life for citizenry. However, the decision support systems associated with new urban intelligence functions and related simulation models and optimization and prediction methods are still in their infancy [6, 12], and also much needs to be done to provide the raw material for the development and implementation of such functions across multiple urban domains.

In addition, with the projected advancements and innovations in big data computing and underpinning technologies, the process of building intelligence functions will shift from top-down (expert and professional organizations) to engaging citizens with experts due to the complexity underlying urban planning, design, development, and governance in the context of sustainability. This entails integrating databases and models from across various urban domains for supporting the development of this sort of integrated intelligence functions, with new or refashioned ways at different levels, including visualization of data and urban sustainability problems, using tools for informing and predicting the impacts of future sustainability scenarios, and engaging citizens and their useful, relevant recommendations, all into a form of a holistic system that operates in accordance with sustainability requirements at various spatial and temporal scales [12].

Bibri [13] examines and discusses this evolving approach to urbanism in terms of computerized decision support and making, intelligence functions, simulation models, and optimization and prediction methods. It also highlights the potential of the integration of these advanced technologies for facilitating the synergy between the operational functioning, planning, design, and development of smart sustainable cities for the primary purpose of improving, advancing, and maintaining their contribution to the goals of sustainable development. Indeed, at the core of smart sustainable urbanism is the interaction or cooperation of these urban practices to produce a combined effect greater than the sum of their separate effects in the context of sustainability. In this respect, urban planning determines the way urban structures and forms should be designed, which shapes urban operational functioning that in turn drives urban development. This entails using advanced technologies, notably big data computing, as an enabler for such synergy as well as a determinant of its outcomes. This is owing to the underlying powerful engineering solutions as a set of novel applications and sophisticated approaches. Big data analytics and related simulation models and optimization and prediction methods might completely redefine urban problems, as well as offer entirely innovative opportunities to tackle them on the basis of new urban intelligence and planning functions, thereby doing more than merely enhancing existing urban practices.

Big data applications and related issues

Key practical and analytical applications for urban systems and domains

Smart sustainable cities are increasingly being permeated with big data technologies and their novel applications in terms of their systems and domains [9, 12, 15]. The smart dimension of such cities can be seen as a new ethos added to the era of sustainable urbanism in response to the rise of ICT and the spread of urbanization as major global shifts at play today. The characteristic spirit of the era of smart sustainable urbanism is manifested in the behavior and aspiration of smart sustainable cities towards embracing what big data computing has to offer in order to bring about sustainable development and achieve sustainability. This is due to the tremendous potential of this advanced form of ICT for adding a whole dimension to sustainability in an increasingly technologized, computerized, and urbanized world. The range of the emerging big data applications as novel analytical and practical solutions that can be utilized in this regard is potentially huge, as many as the case situations where big data analytics may be of relevance to enhance some sort of decision or insight in connection with urban systems and domains. In the sequel, the most common big data applications are identified and enumerated in relation to the key systems and domains of smart sustainable cities, and their sustainability effects are elucidated, which are associated with the underlying functionalities pertaining to urban operations, functions, services, designs, strategies, and policies in the context of such cities, as illustrated in Table 1. However, they are by no means, or

Table 1 Key analytical and practical applications of big data technology for multiple urban domains

Urban systems and domains	Big data applications: operations, functions, services, designs, strategies, and policies, in addition to analytical questions and advanced forms of knowledge
Transport	Monitoring and analyzing road conditions and traffic jams to detect accidents early on and then quickly responding to them by providing alerts and road assistance, thereby reducing or avoiding them and ensuring safety to drivers
	Controlling traffic flows and predicting traffic conditions with the aim to reduce roads' congestion by opening new roads and directing vehicles to alternative ones, thereby improving traffic patterns as well as enhancing or re-engineering transport infrastructure on the basis of historical congestion data
	Using open-source frameworks to implement large-scale agent-based simulation models where different scenarios can be supported by these models, such as air pollution from traffic
	Explaining why traffic significantly varies from 1 hour or day to another even if demand profiles are similar, and how and the extent to which this may affect energy consumption patterns and concomitant GHG emissions levels accordingly
	Predicting spatiotemporally the development and propagation of traffic congestion with small errors, and explaining how the severity of these effects can be stronger in case of non-recurrent events (e.g. accidents), as well as how this can affect the productivity and resilience of transportation systems
	Helping to understand whether or the extent to which the real urban traffic can be considered an equilibrium system, equilibrium conditions with small variations, with respect to cost functions as well as how people really make choices in transportation networks for long periods and how these choices affect the development and propagation of traffic congestion in such networks
	Providing effective ways to identify the macroscopic observables and control parameters that are of influence on individual decisions and integrating them in agent-based simulation models, based on the large number and variety of trajectories and disaggregated traffic data in different locations and of different sizes
	Modeling the traffic evolution under strong or significant changes of network topologies
	Calculating and analyzing the costs and environmental impacts of the transportation choices or decisions of people, combining all modes of transit
	Interconnecting various components of transportation systems (vehicles, infrastructure, drivers, roads, networks, parking spaces, etc.) for enhancing the control, management, and optimization of different processes (in relation to, for example, energy efficiency, GHG emissions, land use, etc.)
	Providing location-based services related to on-board navigation systems, which allows effective use of existing transport infrastructure and network and thus cost- and time-efficient routes. This in turn minimizes traffic congestion
	Addressing equity and inclusion issues in urban transport using smartphone apps and thus playing a key role in creating and mainstreaming socially sustainable urban transport
	Providing proximity-based services showing information when passengers really need it and thereby enabling them to choose different modes of transport in real time
	Enhancing transportation system efficiency by influencing personal travel behavior decisions using advanced platforms and smartphone apps
	Providing visibility into transit system performance based on cloud-based solution, and helping cities make better decisions about transportation by combining big data and spatial analytics
	Advanced parking allows efficient management of multiple parking spaces using and integrating sensors, as well as access to real-time and historical data and making optimal use of parking resources
	Gathering, integrating, and delivering the data on parking spaces by combining Wi-Fi infrastructure with IP cameras, sensors, and smartphone apps, and then providing visibility into parking analytics, including usage and vacancy periods, which can help with long-term city planning
	Enabling an integrated solution to the parking search problems, a location-based smart application which monitors and controls sensors deployed on the curb-side, and communicates the information in real time to the drivers

Table 1 (continued)

Urban systems and domains	Big data applications: operations, functions, services, designs, strategies, and policies, in addition to analytical questions and advanced forms of knowledge
Mobility	Finding answers to many challenging analytical questions about travel or mobility behavior, such as: What is the spatiotemporal distribution of individual travel following the most popular itineraries? How do individual behave when approaching a key attractor, such as a central station and airport? How can we predict areas of dense traffic in the near future? How can we predict travel behavior in mixed-land use areas across spatial and over different temporal scales? How can we classify mobility behavior in high density areas? How can we classify travel behavior according to some contextual variables (e.g. spatiotemporal setting)? How can we predict areas of frequent cycling and walking mode in the near future? How can we find useful travel behavior categories or collective mobility patterns? How can we find correlation between mobility modes and environmental and life quality indicators?
	Explaining how travel behavior or mobility mode is related to the network topology, and how small or large perturbations in demand profiles and network characteristics affect the choices of individuals concerning routes, modes, and departure times
	Explaining how urban design features and related planning tools affect the choices of people in terms of travel mode, behavior, and route, and how this in turn affects social structures and economic networks
	Gathering, integrating, and analyzing real-time mobility data and data from large-scale datasets that can simultaneously record and calibrate dynamical traces of individual and collective mobile movements across various spatial scales and over different temporal scales to understand the dynamic interplay between individual and collective mobility and social interactions
	Using big mobility data to scrutinise different spatiotemporal patterns together with the intensity and frequency of social interactions as well as social structures, thereby coupling mobility patterns and social networks, which can edge towards understanding and studying the evolutionary dynamics of cities as social spheres and their evolving borders
	Analyzing travel behavior and mobility modes together with transport systems and networks for discovering patterns, making correlations, and then acting upon the results by deploying them across different decision support systems
	Enabling new business models such as Mobility-as-a-Service, such as car sharing, bike sharing, and driver service (as well as premium parking and city parking)
	Enabling local authorities to monitor and respond to mobility in real-time manner
	Improving the different aspects of physical and virtual mobility for effective spatial and non-spatial accessibility to opportunities, services, and facilities
	Enabling complex knowledge discovery processes from the raw data of individual trajectories up to high-level collective mobility knowledge, capable of supporting the decisions of mobility and transportation administrators in relation to different aspects of sustainability
	Advancing the content of social media to extract useful information that might be linked to new schemes for mobility management. Social media data will come on stream that is likely to be more focussed as social media technology becomes widespread
	Allowing seamless, efficient, and flexible travel across various modes, i.e., multi-modal transport system. For example, a multimodal trip planner allows users to schedule transit, travel, and map information, and gives detailed step-by-step directions alongside interactive route maps and also details of public transport services required and transfer information
	Providing hassle-free usage of multiple modes of shared and public transport
	Enabling citizens to spend less time in traffic and more time for important things in life, to have flexibility to use the best-fitting transport mode, to enjoy safer and sustainable transport system, and to benefit from lower costs, as well as allowing cities to reduce or optimize the use of land resources

Table 1 (continued)

Urban systems and domains	Big data applications: operations, functions, services, designs, strategies, and policies, in addition to analytical questions and advanced forms of knowledge
Energy	Finding answers to several analytical questions about energy usage levels and consumption patterns, such as: How can we predict energy consumption increase and decrease in the near future? How can we predict or characterize urban energy usage in dense and/or mixed-land use areas? How can we predict or characterize household energy consumption? How can we predict GHG emissions and their environmental impacts in the near future? How can we predict urban energy usage over different temporal scales?
	Allowing citizens to have access to live energy prices and to adjust their use accordingly
	Enabling the use of pricing plans in accordance with energy demand and supply models
	Reorganizing energy demand and supply using advanced pricing and billing mechanisms, based on the energy market and production
	Providing incentives to the users and consumers that save energy, and creating other incentives to use renewable or carbon-neutral energy at a certain time by offering a better price for electricity on a windy or sunny day
	Self-optimizing and -controlling energy consumption through integrating sensing and actuation systems in relation to different kinds of appliances and devices for balancing power generation and usage
	Enabling distributed energy systems to become self-managing and self-sustaining, as well as services in the energy market to become dynamically reorganized and coordinated
	Enabling new mechanisms for trade on the basis of supply and demand in the energy market
	Allowing consumers to manage their usage based on what they actually need and afford
	Enabling users to remotely control their home appliances and devices based on the IoT, and providing them with advanced functions like scheduling, programming, and reacting to different contextual situations
	Controlling millions of connected distributed energy resources across the Internet using demand response optimization and management systems
	Allowing users and consumers to precisely estimate rooftop solar electric potential (PV panels) for almost every building by a simple click or by inputting an address using an interactive online rooftop solar mapping tool
	Enabling energy systems to gather and act on near real-time data on power demand, generation, and consumption from end-user connections (information about producers and consumers' behavior)
Power grid	Supporting decision-making pertaining to the generation and supply of power in line with the actual demand of citizens and other city constituents to optimize energy efficiency and thus achieve energy savings
	Optimizing power distribution networks associated with energy demand and supply
	Monitoring and analyzing energy consumption and GHG emissions levels in real time across several spatial scales and over different temporal scales, with the purpose to curb energy usage and thus mitigate environmental impacts, as well as enhancing the performance and effectiveness of the power system
	Managing distribution automation devices to improve the efficiency, reliability, and sustainability of power production and distribution
	Avoiding potential power outages resulting from high demand on energy using dynamic pricing models for power usage by increasing charges during peak times to smooth out peaks and applying lower charges during normal times
	Avoiding the expensive and carbon-intensive peaks in power grid using new ways of coordination with regard to the overall ensemble of users and consumers and provide dynamic pricing schemes
	Enabling power distribution based on a community or neighborhood model instead of a broadcasting model
	Improving coordination and planning around power generation from renewable energy plants depending on wind or sun, as good estimations of power generation from wind, solar panels, and photovoltaic plants can be made in advance

Table 1 (continued)

Urban systems and domains	Big data applications: operations, functions, services, designs, strategies, and policies, in addition to analytical questions and advanced forms of knowledge
Environment	Improving the environment through increasing air quality and reducing noise pollution and GHG emissions by deploying and setting up stations across the city as well as mounting sensors on bike wheels and cars for measuring and analyzing air data and acting upon the obtained results
	Providing information about air quality extracted from cities' preexisting environmental monitoring networks using Web applications, a rapid and effective technological answer to the needs of people with special sensitivity to environmental allergies
	Connecting data, citizens, and knowledge to serve as a node for building open indicators and distributed tools, and thereafter the collective construction of the city for its own inhabitants, using an open-source platform for crowd-sourced environmental monitoring
	Predicting future environmental changes based on spatial and temporal geographic maps, and detecting natural disasters to save lives and resources
	Removing many types of pollutants detrimental to the pubic health through pervasive sensors deployed for detecting pollution in the air and water systems
	Monitoring the urban climate and analyzing related data to discover the origins of GHG emissions, as well as measuring and monetising cities' CO_2 emissions by combining satellites and ground sensors' data
Buildings	Monitoring and optimizing the operational energy use within residential, industrial, public, and commercial buildings by means of an integrated system of sensors and actuators associated with the mechanical, electrical, and electronic systems of heating, ventilation, and air-conditioning (HVAC). This can even be more effective if implemented across several spatial scales and over different time spans
	Monitoring and managing the environmental conditions in buildings as well as demand control ventilation and control temperature, in addition to the energy system performance
	Minimizing heat/cooling losses and monitoring CO_2 emission levels
	Managing window and door operations and providing lighting based on occupancy schedules
	Allowing the digital and physical objects in buildings to, based on a sensor and actuator system, process data, self-configure, and make independent decisions pertaining to their operations and functions by reacting to the physical environment
	Building energy benchmarking through visualization tools that make it possible to view energy usage for individual buildings using maps, charts, and statistics to hone in on a region of interest and view energy usage
Infrastructures	Monitoring and controlling the operations and structural conditions of urban infrastructures, including roads, railway tracks, bridges, tunnels, power grids, and water systems to minimize risk, decrease cost, and ensure safety and service quality, thereby improving incident management, emergency response coordination, service efficiency, and operational costs reduction
	Allowing for scheduling repair and maintenance activities in an efficient manner by coordinating tasks between different service providers and operators of urban infrastructures and facilities
	Monitoring, managing, and enhancing waste and water systems and related distribution networks
	Relating urban infrastructures effectively to their operational functioning through control, automation, optimization, and management enabled by data analytics
	Smart waste systems designed for public spaces, which comprise modular components that enable cities to deploy waste and even compost stations that respond to the needs of each station's locations
	Increasing efficiency and transparency in waste management based on sensor solutions, through tracking container fill-levels and optimizing pickup routes, thereby reducing the environmental footprint of the waste
	Enabling a dynamic routing system for waste management using software tools and sensors to lower costs of services by building, delivering, and analyzing the most efficient routes for a fleet
	Using simulation models to estimate water supply and demand. Users can explore how water sustainability is influenced by different scenarios of regional growth, climate change impacts, drought, and water management policies

Table 1 (continued)

Urban systems and domains	Big data applications: operations, functions, services, designs, strategies, and policies, in addition to analytical questions and advanced forms of knowledge
	A cloud-based platform for data-driven water demand management intended, which maximises water-use efficiency and improve financial forecasting accuracy through engaging citizens
	Smartening up urban metabolism by collecting, processing, and analyzing a large amount of data pertaining to the use of material and energy resources as well as waste generation, and then identifying and suggesting alternative routes of development that would reduce the ecological footprint of the city while ushering in new relations with the immediate surrounding lands and water
Urban planning	Relating the urban infrastructure to its planning through monitoring, analysis, modeling, simulation, prediction, and intelligent decision support associated with engineering, strategy development, and policy design
	Fully integrating urban systems, coordinating urban domains, and coupling urban networks to enhance land use and development, optimize resource utilization, reduce city costs, and streamline processes
	Integrating urban systems in terms of operations, functions, services, strategies, and policies for more effective and efficient functioning, management, and planning
	Helping cities quickly identify underperforming domains, evaluating improvement and cost-saving potential, and prioritising domains and actions for energy and performance efficiency interventions using decision-support tools
	Developing intelligence functions for the efficiency of energy systems, the improvement of transport and communication systems, the effectiveness of distribution networks, the optimal use and accessibility of facilities, and the optimization of ecosystem and human service provision
	Using urban simulation models to aid urban planners and strategists in understanding under what conditions urban systems and domains may fail to deliver or underperform at the level of sustainability and what to do about it
	Using advanced modeling and simulation systems to predict changes and forecast potential problems, and accordingly to enhance current designs, mitigate environmental impacts, and avoid public health risks
	Predicting population growth and socio-economic changes and needs and thus devising more effective strategies in terms of seamlessly integrating advanced technologies and sustainable urban design and planning principles
	Grouping, characterising, and profiling citizens in relation to sustainable lifestyles for inducing behavioral changes and improving the quality of life and well-being
	Enabling joined-up and integrated planning which allows system-wide effects to be tracked, understood, analyzed, and built or integrated into the very designs and responses that characterize urban operations, functions, and services
	Analyzing policies and their impact and effectiveness with the aim to improve or change them according to new social and urban trends and major global shifts
	Enabling space-time convergence in planning (and design) methods based on sophisticated simulation models using computer models of various kinds that operate at various spatial scales and over different time spans as to predicting changes and understanding how cities function in connection with land use, densification, public transport, location of physical activities, and so on
	Enabling short-termism in city planning—what takes place in cities measured, evaluated, modeled, and simulated over days or months instead of years or decades
Urban design	Monitoring, analysing, and evaluating the environmental and social performance of urban sustainability strategies (typologies and design concepts) in terms of the extent to which they contribute to sustainable development goals
	Analyzing and evaluating the relationship between individual and collective mobility and environmental and socio economic performance assumed to be achieved through urban sustainability strategies, i.e., spatial and urban proximity, contiguity, agglomeration, and/or connectivity
	Enhancing the performance and practicality of urban sustainability strategies through augmenting them with smart applications and services, or improving their integration based on different spatial scales using simulation models
	Optimizing sustainable urban design in terms of the principled set of organized and coordinated spatial patterns and structures and physical arrangements with regard to the contribution to sustainable development goals

Table 1 (continued)

Urban systems and domains	Big data applications: operations, functions, services, designs, strategies, and policies, in addition to analytical questions and advanced forms of knowledge
	Informing future designs on the basis of predictive insights and forecasting capabilities enabled by the aggregated urban simulation models of different situations of urban life thanks to the recent advances in, and pervasiveness of, sensor technologies and their ability to provide information about medium- and long-term changes
	Facilitating the application of systems thinking and complexity sciences to solve the existing wicked problems associated with sustainable urban design, such as the distribution of sustainable typologies across several spatial scales
	Allowing citizens to view the location and size of their city's trees, submit information to help tag them, and advocate for more trees in their area, based on an interactive Web application that measures cities' green spaces. This relates specifically to greening which is a key concept of sustainable urban design
Academic research	Overcoming the limitations of 'small data' studies associated with such data collection and analysis methods as surveys, focus groups, case studies, participatory observations, interviews, content analyzes, and ethnographies, including high cost, infrequent periodicity, quick obsolescence, inaccuracy, incompleteness, as well as subjectivity and biases
	Overcoming the inherent deficiencies of limited samples of data that are tightly focused, time- and space-specific, restricted in scope and scale, and relatively expensive to generate and analyze, which affects the robustness of research results
	Drastically changing the way the research data can be collected, processed, analyzed, modeled, and simulated within various academic and scientific research domains so as to make decisions easier to judge and more fact-based in relation to urban operations, functions, strategies, plans, policies, and other practices
	Completely redefining urban problems and understanding them in new ways, as well as enabling entirely novel ways to tackle them, thereby doing more than just enhancing existing practices, especially in relation to sustainability
	Transforming and advancing knowledge based on the deluge of urban data that seeks to provide more sophisticated, wider-scale, finer-grained, real-time understanding, and control of various aspects and complexities of urbanity
	Enabling well-informed, knowledge-driven practices based on advanced forms of intelligence with regard to the operational functioning, management, design, planning, and development of urban systems in the context of sustainability
	Promoting and facilitating openness and access to public data and their integration with the private information assets for use in city analytics and big data studies to advance the knowledge about sustainability
	Advancing environmental indicators and objective targets for the purpose of monitoring progress, implementing strategies, allocating resources, and increasing the accountability of stakeholders
	Enabling novel and harmonising urban-level metrics for monitoring the goals of sustainable development through more objective and robust indicators and targets developed and continuously enhanced based on big data analytics
	Exploring and discovering laws and principles of sustainability pertaining to environmental and socio-economic aspects, and allowing an inference of stakeholders' responses to operations, functions, services, strategies, designs, and policies in relevance to sustainability
Governance	Enabling governments to establish, formulate, and implement more effective policies based on the enhanced insights (trends, shifts, lifestyles, environmental concerns, etc.) resulting from the useful knowledge that is extracted from large masses of data on citizens and their behavior and tendencies in terms of sustainability, education, and healthcare
	Facilitating platforms for shared knowledge for ensuring democratic governance and informed participation by allowing citizens to get more involved and engaged and to blend their knowledge with that of urban experts
	Enabling widespread participation of citizens in relation to several functions of city governance and planning
	Building up e-governance tools and connecting the cooperative participation with the personal knowledge of citizens with respect to promoting environmentally friendly activities, such low-carbon mobility, sustainable travel behavior, emission-free transport, demand-based utility, incentive-based energy usage, etc.

Table 1 (continued)

Urban systems and domains	Big data applications: operations, functions, services, designs, strategies, and policies, in addition to analytical questions and advanced forms of knowledge
	Organizing and coordinating various governmental agencies with common interests towards collaboration, integration, optimization, and further development
	Enabling responsive e-government to rich, dynamic, and real-time data for efficient service delivery, enhanced interaction, and empowered citizenry, or more effective government management. This can be enabled through wireless communication networks, data processing platforms, cloud/fog computing, distributed computing, and mobile computing that have the ability to transform relations with citizens and other relevant arms of government
	Reducing corruption, enhancing transparency, providing convenience, decreasing costs, achieving equity and inclusion, and promoting citizen empowerment through advanced e-government
Healthcare	Predicting epidemics, disease outbreaks, and cures, as well as preventing or avoiding preventable death
	Flagging potential health issues frequently or on a demand basis by monitoring and analyzing complex occurrences and events
	Enabling efficient healthcare systems that provide permanent monitoring, traceability of patients and their medical
	devices, and full accessibility of their data
	Using monitoring devices or specialized sensors to quickly detect anomalies, recognise patients' behaviors, and identify and predict changes in their normal parameters
	Enabling remote health monitoring systems by observing patients outside of conventional medical or clinical settings, thereby reducing healthcare delivery costs
	Integrating clinical devices into living spaces to enable patients to communicate health data to hospitals or medical centers using smartphone apps
	Enabling efficient emergency notification systems by facilitating the dissemination of messages to many groups of people alerting or notifying them of an extant or pending emergency situation
	Connecting medical centers, patients, and doctors with data repositories and health monitoring software tools
	Enabling doctors to detect the warning signs of serious illness during the early stage of treatment
	Facilitating rapid changes in the models of treatment delivery and many decisions behind these changes
	Using consumer devices to encourage healthy living, especially for senior or elderly citizens
	Mining DNA of citizens to discover, model, simulate, and improve health aspects
	Enabling responsive and proactive environments that allow for easy participation of citizens in their own healthcare management, as well as a remote monitoring of physical activity and well-being and e-inclusion for citizens with physical disabilities
	Mainstreaming and tailoring care services, enhancing diagnosis processes, and providing precautionary and proactive care services as well as accurate, appropriate, and history-aware responses to health issues
Public safety	Monitoring urban environments to alert citizens and informs public services of potential risks and vulnerabilities
	Contributing to risk assessment and hazard identification and providing immediate response to perceived threats
	Allowing or denying access to certain individuals to public places as well as preventing potential unrest and thereby protecting public places and citizens
	Predicting natural disasters to save lives and resources
	Enabling a data-driven approach to understanding and addressing transportation-related health issues using an online database and analytical tool to inform public and private efforts to improve transportation system safety and public health
	Tracking and predicting pollution or spread of chemicals in certain urban areas to prevent or mitigate adverse health effects by notifying citizens to evacuate or avoid those areas

Table 1 (continued)

Urban systems and domains	Big data applications: operations, functions, services, designs, strategies, and policies, in addition to analytical questions and advanced forms of knowledge
Education	Improving education and learning methods in terms of efficiency, effectiveness, and richness through adaptable, personalised, flexible, and pertinent processes and services
	Optimizing evaluation methods as to finding out whether the allocated resources are producing the right results or the allocation is being done efficiently, as well as whether there is a need for the integration and coordination of these resources for further effectiveness, efficiency, and cost reduction
	Enhancing learning attitudes and behaviors by analyzing interactions with the different sorts of academic material and reactions to academic curriculums, and the acting upon the obtained results
	Enhancing the existing, or creating new, education and learning practices based on deep insights into emerging social trends and global shifts, extracted as a result of big data analytics
	Allowing citizens to actively engage in, and benefit from, the kind of leaning environments that are conducive to the adaptation to societal development and change in terms of new scientific paradigms, emerging intellectual transitions, discontinuities, disruptive innovations, technological advancements, and so on
	Continuously advancing knowledge production, teaching, and learning methods to deliver and disseminate the most relevant and useful forms of education with regard to current societal needs and market demands
	Reducing private education cost, providing life-long learning and eduction opportunities, and enabling self-learning and creative education

intended to be, exhaustive. Moreover, they are synthesized and distilled from the technical literature on smart cities and smart sustainable/sustainable smart cities [8, 9, 11, 12]. Of relevance to add, as to the technical processes, tools, and other details underpinning the functioning of big data applications, the interested reader can be directed to Bahga and Madisetti [4], one of the many books available out there on the topic, for a detailed account from a general perspective, and to Bibri [16] for an overview focusing mainly on smart sustainable cities.

Relevant policy and technology issues

Big data analytics and related applications provide a very rich nexus of possibilities for enhancing urban operations, functions, services, strategies, and policies in terms of sustainability, efficiency, and resilience, which comes with benefits for the quality of life and well-being of citizens. These benefits are associated with smart sustainable cities. One of the core ideas underlying the development and implementation of big data applications in such cities is to harness solutions, improve services, integrate approaches, and enhance outcomes with respect to urban practices and city life [9]. One way of achieving this is through integrating urban systems, coordinating urban domains, and coupling socio-economic networks using more effective ways of monitoring, understanding, analysing, planning, and governing modern cities. Overall, exposing big data via a socially synergistic and environmentally substantive as well as evolvable, extensible, dynamic, scalable, and reliable big data ecosystem in smart sustainable cities offers a wide range of opportunities with regard to sustainability dimensions and their integration. The advanced forms of ICT and the underlying computational and data analytics are as primordially needed as the interdisciplinary and transdisciplinary knowledge in sustainable smart urban development as a complex area of study.

There is huge potential for using big data analytics to address many of the pressing issues and wicked problems involved in smart sustainable cities through innovative solutions for and sophisticated approaches to, and new practices of, decision-making informed by high levels of intelligence enabled by the analytical outcome of the urban data deluge. Thus, this advanced form of ICT offers such cities more capabilities and resources that can allow them to realize their full potential for meaningful progress as urban development models in response to the upcoming Exabyte Age and urbanization era. In this regard, understanding the characteristics of such cities, identifying the complex sustainability and urbanization issues, and acknowledging the potential of big data analytics and its application facilitate the process of putting in place and maintaining what is technologically and socio-politically required to develop, apply, and mainstream the needed smart applications.

The three main components that policymakers can explore as to how to plan and construct smart sustainable cities are: the construction of public infrastructure, the construction of public platform for such cities, the construction of application systems based on big data analytics, the construction of innovation labs, and the construction of participatory governance models. These all involve issues and challenges that constitute future fields of study. Those components are to be addressed and relevant solutions to be devised, as the existing plans evolve and new ones are developed in response to new urgencies requiring swift actions, as well as more R&D activities and efforts are made in relation to city development in terms of the implementation of cutting-edge technologies together with sustainable design concepts and typologies. This requires clear, reliable, strategic, and astute plans for city development and realisation, rather than piecemeal initiatives, scattered projects, or standalone programs. In this regard, the requirements and objectives of smart sustainable cities for technological, physical, and social infrastructures must be taken into account in such plans, instead of treating each part as its own silo. This holistic approach into city development provides a clearer and more focused perspective on what is needed and of priority to address, and will result in more rounded solutions (well developed in all aspects or complete and balanced for the city), rather than isolated islands of components and applications that could hardly connect with each other. Hence, the efforts to be poured into the development of smart sustainable cities should concentrate on creating a roadmap for success that covers several phases, including, but not limited to, the following:

- Create a mission statement that can guide the development of smart sustainable city and help fulfill its long-term goal.
- Set up the direction of such city by crafting its vision and identifying its strategic and operational objectives, in particular in relation to technological innovation and sustainable development.
- Establish policies, regulations, and rules, as well as determine resources and expertise required to govern big data usage and the use of other advanced forms of ICT.

- Build public infrastructures and platforms based on big data analytics and its application to support innovative smart applications. This entails analyzing and assessing the current situation and determining the necessary transformations or changes to reach the desired outcomes in terms of technology and design in line with the vision of sustainability.
- Identify priorities with regard to different technology and sustainability dimensions and use them to determine the most important and relevant city components and applications that would offer the greatest effects with the smallest investment possible.
- Integrate city infrastructures and activities in terms of operations, functions, services, strategies, and policies and big data applications to develop more efficient urban life and more effective urban environment.
- Optimize continuously the operating and organizing processes of urban life and environment based on new advances in big data analytics and its application to identify the needed improvements or changes.
- Stimulate and realize new opportunities for R&D by monitoring current progress and its effect and the potentially arising issues and challenges, and thereby creating new requirements and objectives.

Evidenced by the urban world evolving increasingly into becoming fully technologized and computerized based on big data, the prospect has become clear that smart sustainable cities will be enabled and developed using the core enabling technologies of big data analytics, and hence related novel applications to effectively and efficiently cater for the needs of diverse urban constituents as well as meet their aspirations in an unsustainable and rapidly urbanized world. This might well call for funnelling huge investments into the kinds of resources, infrastructures, platforms, and expertise that are required to support the construction and deployment of the core enabling technologies of big data analytics throughout the various design and development stages of smart sustainable cities. This strategic move is deemed essential to reap the sustainability benefits in terms of environmental and socio-economic gains in such cities. To help optimize the city design and development as an endeavor and minimize its costs, it is recommended to include important activities in the process, some of which are presented below:

- Developing advanced modeling and simulation systems to help predict potential problems and forecast possible changes, with the primary purpose of mitigating or avoiding any risks that might arise, as well as reducing the implementation and testing costs following city design and development. Simulation models and prediction methods have great potential to modernize smart sustainable city design and development in the future [8, 10]. Indeed, using simulations is generally cheaper, safer, and faster than studying real-time processes or conducting real-world experiments. Also, simulations allow a flexible configuration of the parameters within the different sub-processes found in the operational application field of smart sustainable cities as complex systems and dynamically changing environments.

- Learning and benefitting from previous experiences in sustainable smart urban planning and development to adopt best practices and follow successful models and avoid problematic approaches.
- Benefitting from the eminent experts, scholars, and researchers in the field to investigate new possibilities for more advanced technological systems of suitability to the objectives of smart sustainable cities with regard to sustainability.
- Investigating the relevance of big data applications to such cities in this direction, an understanding which will help incorporate the right data into the right applications to make accurate, knowledge-driven decisions and implement them to enhance and optimize urban operations, functions, services, designs, strategies, and policies in line with the goals of sustainable development.

A novel architecture and typology of data-driven smart sustainable cities

Specialized constituents for making up a whole

There exist a range of city architectures that essentially aim to provide the appropriate infrastructure for big data systems and applications for steering urban processes and enhancing urban practices, and whose components serve to form, compose, or make up a whole. These architectures typically influence the relationship between their components and urban constituents and entities. The architecture of the data–driven smart sustainable city illustrated in Fig. 2 entails specialized urban, technological, organizational, and institutional elements dedicated for improving, advancing, and maintaining the contribution of such city to the goals of sustainable development. It is derived based on the outcome of the above thematic analysis and technical literature. This outcome justifies the relationship between the different layers of the architecture. It is worth pointing out that the layered approach to this architecture is motivated by the scientific literature on smart cities, sustainable cities, and smart sustainable cities. However, a layered approach is only one among other approaches to consider in this regard.

Furthermore, underlying the idea of the data-driven smart sustainable city is the process of drawing all the kinds of analytics associated with urban life into a single hub, supported by broader public and open data analytics. This involves creating a city-wide instrumented or centralized system that draws together data streams from many agencies (across city domains) for large scale analytics and then direct it to different centers and labs. Urban operating systems as part of cloud computing infrastructure explicitly link together multiple urban technologies to enable greater coordination of urban systems and domains. Urban operations centers attempt to draw together and interlink urban big data to provide integrated and holistic views and synoptic city intelligence through processing, analyzing, visualizing, and monitoring the vast deluge of urban data that is used for real-time decision-making pertaining to sustainability using big data ecosystems. Strategic planning and policy centers serve as a data analytic hub to weave together data from many diverse agencies to control, manage, regulate, and govern urban life more efficiently and effectively in relation to sustainability. This entails an integration that enables systemwide effects to be understood, analyzed, tracked, and built into the very designs

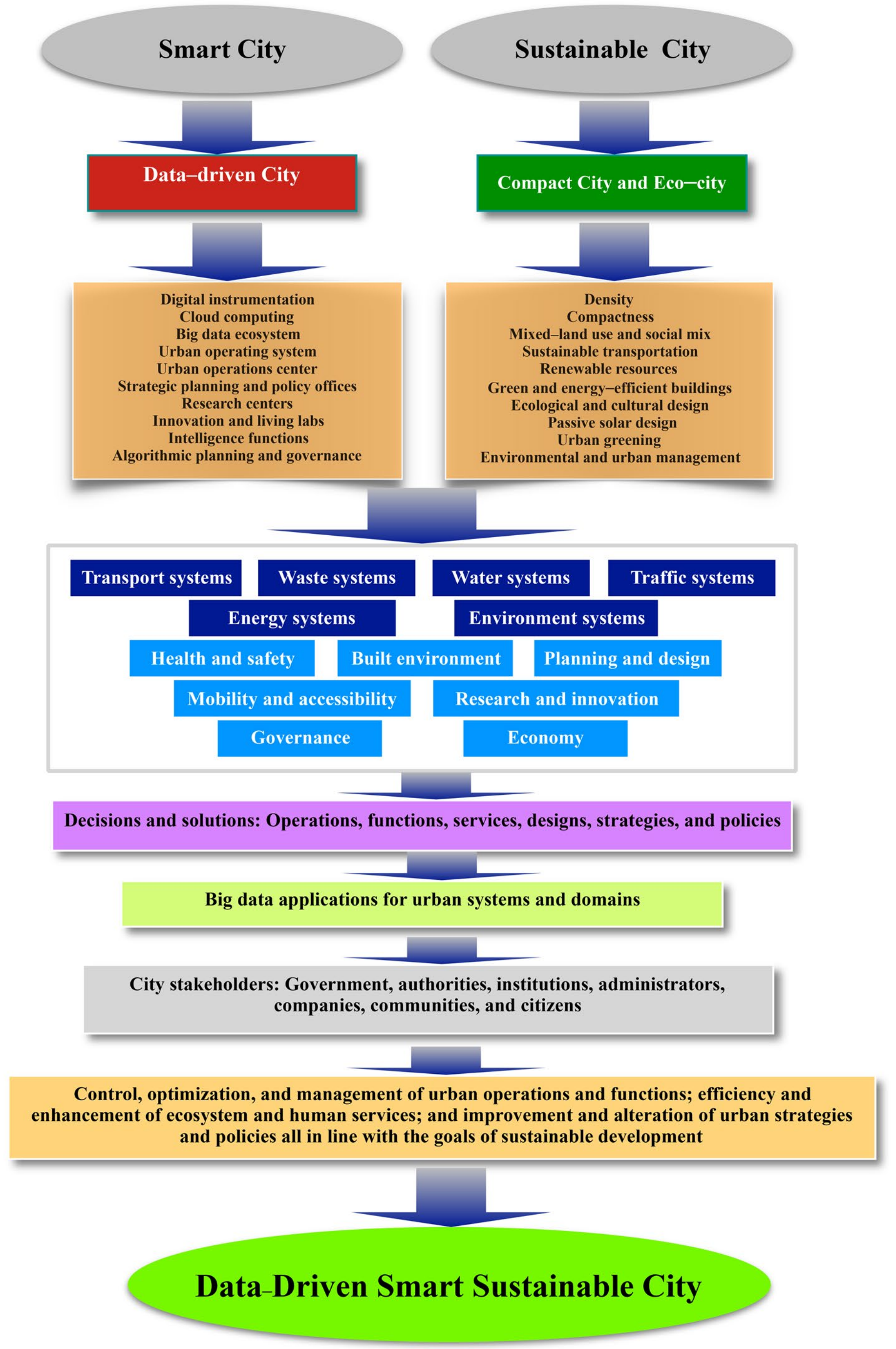

Fig. 2 An architecture of the data-driven smart sustainable city

and responses that characterize urban operations, functions, and services. As far as research centers and innovation labs are concerned, they are associated with research and innovation for the purpose of developing and disseminating urban intelligence functions.

Typological dimensions and functions

As a leading paradigm of and holistic approach to urbanism, data-driven smart sustainable cities represent a class of cities which are composed of and monitored by ICT of ubiquitous and pervasive computing and underpinned by big data technology and its novel applications that aim at harnessing physical, economic, and social infrastructures as well as leveraging knowledge and conserving resources through enhanced and optimized operational functioning, planning, design, development, and governance. This occurs in ways that ensure environmental integration, social justice, and economic regeneration as fundamental goals of sustainable development towards achieving sustainability. Smart sustainable cities as an integrated approach to urbanism takes multiple forms of combining the strengths of sustainable cities and smart cities based on how the concept of smart sustainable cities can be conceptualized and operationalized, as well as on the multiple processes of, and pathways towards achieving, their status. As a corollary of this, there is a host of opportunities yet to explore towards new approaches to smart sustainable urbanism. This will result in the multiplicity of models of smart sustainable cities in the future. Below is an exemplar of a model of data-driven smart sustainable cities (Table 2) encompassing nine distinct dimensions and functions. This model also shows how various urban systems and domains might connect up as shaped by the use of big data technology and its novel applications.

Challenges and concerns

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

The rising demand for big data analytics and its core enabling technologies, coupled with the growing awareness of the associated potential to transform the way the city can function in the context of sustainability, comes with major challenges and concerns related to the design, engineering, development, implementation, and maintenance of data-driven applications in smart sustainable cities. The challenges are mostly computational, analytical, and technical in nature, and sometimes logistic in terms of the detailed organization and implementation of the complex technical operations involving the installation and deployment of the big data ecosystem and its components as part of the ICT infrastructure of such cities. They include, but are not limited to, the following, as compiled in Table 3 from Bibri [12]:

For a detailed discussion of the above challenges as well as a number of open issues, the interested reader can be directed to Bibri [8, 11]. Of particular importance to highlight is that smart sustainable urbanism, urban science, and big data computing and the

Table 2 A typology of data-driven smart sustainable city dimensions and functions

Smart sustainable built environment	Smart sustainable citizens	Smart sustainable governance
Data-driven compactness Data-driven density Data-driven mixed-land use Data-driven diversity Data-driven sustainable transportation Data-driven ecological design Data-driven integration of design concepts and typologies at different spatial scales	Cultural enhancement Lifelong learning Creativity Social plurality/cultural diversity Sustainable lifestyles Tolerance and open-mindedness Active involvement in public life Innovative and meaningful use of technology Personal knowledge sharing Motivation for participation	New forms of e-government New modes of operational governance Coordination of governmental agencies towards collaboration, integration, and optimization Evidence-based approach to decision-making, system control, and policy formation Improved models and simulations for future development Democratic processes Public and social services Equity and fairness Transparent, participatory, and accountable government

Smart sustainable mobility	Smart sustainable environment	Smart sustainable living
Spatial and non-spatial accessibility Virtual mobility Balanced mobility and accessibility Car and bicycle sharing Innovative, intelligent, and safe transport systems Walking and cycling Proximity of services and facilities Diversity of commuting modes Efficient, interoperable multi- modal public transport	Green and resilient infrastructure Attractive urban places and images Open urban landscapes Air quality and environment protection Ecological diversity of urban places Sustainable and intelligent resource management	Social cohesion and inclusion Cultural facilities Education facilities Public safety and civic security Housing quality Public utility (water, electricity, gas, etc.) Health conditions Job opportunities Efficient and tailored services Participation and empowerment Well-informed citizenry and fostered creativity

Smart sustainable planning	Smart sustainable economy	Smart sustainable energy
Data-driven local and regional planning Data-driven environmental planning Data-driven transportation planning Data-driven land use planning Data-driven economic forecasting Data-driven policy recommendations Data-driven strategic thinking and development Data-driven research and analysis Data-driven administration	Green entrepreneurship Integration of environmental concerns into economic decision-making Data-driven business processes Optimum balance of technological and human resources in labor market Efficient utilization of resources Green investments Green ICT for economic innovation Sustainable productivity New forms of economic development (e.g. sharing and open data economy)	Integrated renewable solutions Clean/green technology Data-driven grid management Context-aware operation of buildings Dematerialization and demobilization Context-aware operation of appliances Data-driven transport systems Data-driven urban efficiency Context-aware power supply and distribution

underpinning technologies create a number of potential privacy harms for several reasons. Kitchin [36] addresses five reasons, each of which raises significant challenges to existing approaches to protecting privacy (privacy laws and fair information practice principles), namely:

1. Datafication, dataveillance and geosurveillance.
2. Inferencing and predictive privacy harms.
3. Anonymization and re-identi cation.
4. Obfuscation and reduced control.

Table 3 Computational, analytical, technical, and logistic challenges Source: Bibri [12]

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

5. Notice and consent is an empty exercise or is absent.

Adding to the above primarily technological challenges are the financial, organisational, institutional, social, political, regulatory, and ethical ones, which are associated with the implementation, retention, and dissemination of big data across the domains of smart sustainable cities [11]. As an example, controversies over the benefits of big data analytics and its application involve limited access and related digital divides and other ethical concerns about accessibility (see Bibri 11 for an overview). Kitchin [33] provides a critical reflection on the implications of big data and smart urbanism, examining five emerging concerns, namely:

1. The politics of big urban data.
2. Technocratic governance and city development.
3. Corporatization of city governance and technological lock-ins.
4. Buggy, brittle and hackable cities.
5. The panoptic city.

Conclusion

Building smart sustainable cities based on big data computing is of a strategic value as to solving many of the complex challenges and pressing issues of sustainability and urbanization. Many sustainable cities and smart cities across the globe have already started to exploit the potential of big data applications in relation to diverse urban systems and domains. We stand at a threshold of a new era where big data science and analytics is drastically changing the way smart sustainable cities are studied, understood, planned, designed, developed, and governed. The ultimate goal is to improve, advance, and maintain their contribution to sustainability by employing more effective and innovative ways to monitor, understand, probe, and plan them. However, there are currently numerous challenges and concerns that need to be addressed and overcome in this new area of science and technology in relation to smart sustainable urbanism for achieving the desired outcomes.

This paper examined how data-driven smart sustainable cities are being instrumented, datafied, and computerized so as to improve, advance, and maintain their contribution to the goals of sustainable development through enhanced practices. In this respect, different topics have been identified and discussed, namely the integration of data-driven smart cities and sustainable cities, digital instrumentation living labs, innovations labs, urban intelligence functions, urban operating centers and strategic planning and policy offices, data types and the role of open data, and data-driven urbanism and urban science and how they relate to one another from a scientific and scholarly perspective. The essence of the idea of data-driven smart sustainable cities revolves around the need to harness and leverage big data technologies that have hitherto been mostly associated with smart cities but have clear synergies in the functioning of sustainable cities and tremendous potential for enhancing their performance and need to be steered or directed for this purpose so that many new opportunities can be enabled and realized. From a societal standpoint, big data computing and its technological applications are socio-culturally constructed to have a determinant role in instigating major social changes on multiple scales due to its transformational power residing or embodied in its disruptive, synergistic, and substantive effects on different forms of social organization.

Also, this paper highlighted and substantiated the real potential of big data technology for improving, advancing, and maintaining the contribution of smart sustainable cities to the goals of sustainable development by identifying, synthesizing, distilling, and enumerating the key practical and analytical applications of this advanced technology in relation to multiple urban systems and domains with respect to urban operations, functions, services, designs, strategies, and policies. The most common data − driven applications identified include: transport and traffic, mobility, energy, power grid, environment, buildings, infrastructures, urban planning, urban design, academic and scientific research, governance, healthcare, education, and public safety. The potential of big data technology lies in enabling smart sustainable cities to harness and leverage their informational landscape in effectively understanding, monitoring, probing, and planning their systems and environments in ways that enable them to reach the optimal level of sustainability. To put it differently, the use of big data analytics is projected to play a significant role in realizing the key characteristic features of such cities, namely the efficiency of operations and functions, the prudent utilization of natural/environmental resources, the intelligent management of infrastructures and facilities, the improvement of the quality of life and well-being of citizens, and the enhancement of mobility and accessibility.

Moreover, this paper proposed, illustrated, and described an architecture and typology of data-driven smart sustainable cities. Their unique features lie in their novelty in terms of bringing new ingredients and the way they are integrated and affect and shape the relationships between the urban entities specific to smart sustainable cities in light of the use of big data technology and its applicability to sustainability. The proposed architecture and typology are developed in response to the need for improving, advancing, and maintaining the contribution of such cities to the goals of sustainable development.

Concerning the value of this work, the outcome will help strategic city stakeholders understand what they can do and invest in more to advance smart sustainable urbanism on the basis of data-driven solutions and approaches, and also give policymakers an opportunity to identify areas for further improvement while leveraging areas of strength with regard to the future form of such urbanism. In addition, it will enable researchers and scholars to direct their future work to the emerging paradigm of data-driven smart sustainable urbanism, and practitioners and experts to identify common problems and potential ways to solve them, all as part of future research and practical endeavors, respectively.

Lastly, this paper provides a form of grounding for further discussion to debate over the disruptive, synergetic, and transformational effects of big data computing and underpinning technologies on forms of the operational functioning, management, planning, design, development, and governance of smart sustainable cities in the future. Also, it presents a sort of basis for stimulating more in-depth research in the form of both qualitative analyses and quantitative investigations focused on establishing, uncovering, substantiating, and/or challenging the assumptions underlying the relevance of big data technology and its advancements as to accelerating sustainable development.

Abbreviations

AMR: Automatic Meter Reading; BDAS: Big Data Analytics Services; BDIS: Big Data Infrastructure Services; BDPS: Big Data Platform Services; GPS: Global Positioning System; ERP: Enterprise Resource Planning; IaaS: Infrastructure-as-a-Service; NTNU: Norwegian University of Science and Technology; PaaS: Platform-as-a-Service; SDG: Sustainable Development Goal; SaaS: Software-as-a-Service; UN: United Nations; ZEB: Zero Emission Buildings; ZEN: Zero Emission Neighborhoods.

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Authors' contributions

The author read and approved the final manuscript.

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3. Master of Science in computer science with a major in informatics
4. Master of Science in computer and systems sciences with a major in decision support and risk analysis
5. Master of Science in entrepreneurship and innovation with a major in new venture creation
6. Master of Science in strategic leadership toward sustainability
7. Master of Science in sustainable urban development
8. Master of Science in environmental science with a major in ecotechnology and sustainable development
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2. The Shaping of Ambient Intelligence and the Internet of Things: Historico-epistemic, Socio-cultural, Politico-institutional and Eco-environmental Dimensions (301 pages), Springer, 11/2015.
3. Smart Sustainable Cities of the Future: The Untapped Potential of Big Data Analytics and Context-Aware Computing for Advancing Sustainability (660 pages), Springer, 03/2018.
4. Big Data Science and Analytics for Smart Sustainable Urbanism: Unprecedented Paradigmatic Shifts and Practical Advancements (505 pages), Springer 06/2019.

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