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The underlying components of data-driven smart sustainable cities of the future: a case study approach to an applied theoretical framework

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Abstract

The increased pressure on cities has led to a stronger need to build sustainable cities that can last. Planning sustainable cities of the future, educated by the lessons of the past and anticipating the challenges of the future, entails articulating a multi-scalar vision that, by further interplaying with major societal trends and paradigm shifts in science and technology, produce new opportunities towards reaching the goals of sustainability. Enabled by big data science and analytics, the ongoing transformative processes within sustainable cities are motivated by the need to address and overcome the challenges hampering progress towards sustainability. This means that sustainable cities should be understood, analyzed, planned, designed, and managed in new and innovative ways in order to improve and advance their contribution to sustainability. Therefore, sustainable cities are increasingly embracing and leveraging what smart cities have to offer in terms of data-driven technologies and applied solutions so as to optimize, enhance, and maintain their performance and thus achieve the desired outcomes of sustainability—under what has been termed “data-driven smart sustainable cities.” Based on a case study analysis, this paper develops an applied theoretical framework for strategic sustainable urban development planning. This entails identifying and integrating the underlying components of data-driven smart sustainable cities of the future in terms of the dimensions, strategies, and solutions of the leading global paradigms of sustainable urbanism and smart urbanism. The novelty of the proposed framework lies in combining compact urban design strategies, eco-city design strategies and technology solutions; data-driven smart city technologies, competences, and solutions for sustainability; and environmentally data-driven smart sustainable city solutions and strategies. These combined have great potential to improve and advance the contribution of sustainable cities to the goals of sustainability through harnessing its synergistic effects and balancing the integration of its dimensions. The main contribution of this work lies in providing new insights into guiding the development of various types of strategic planning processes of transformative change towards sustainability, as well as to stimulate and inspire future research endeavors in this direction. This study informs policymakers and planners about the opportunity of attaining important advances in sustainability by integrating the established models of sustainable urbanism and the emerging models of smart urbanism thanks to the proven role and untapped potential of data-driven technologies

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in catalyzing sustainable development and thus boosting sustainability benefits.

Keywords: Sustainable cities, Compact cities, Eco-cities, Data-driven smart cities, Data-driven smart sustainable cities, Sustainability, Sustainable urbanism, Smart urbanism, Big data technologies

Introduction

As an irreversible global trend, urbanization involves a multitude of environmental, economic, social, and spatial conditions, which pose unprecedented challenges to politicians, policy makers, and planners. Nonetheless, it can have many positive outcomes by creating changes out of these challenges and as a response to external factors. These changes provide great opportunities for advancing sustainability in terms of applying innovative technologies to use resources more efficiently and control them more safely, to promote more sustainable land use, and to preserve the biodiversity of natural ecosystems and reduce pressure on their services, with the aim to improve economic and societal outcomes. In a nutshell, cities across the globe hold the potential to maximize the benefits of urbanization and offset its negative consequences by relying on emerging and future Information and Communication Technology (ICT). In fact, urbanization has become a popular discourse in urban policy and academic circles across the world due to the rising popularity of smart urbanism and its role in advancing urban sustainability.

As cities represent part of the problems and solutions in the quest for sustainability, they can function as one of the keys in the required transition towards sustainability thanks to their configuration and innovative potential. Therefore, numerous stakeholders and institutions have devoted much attention to sustainable development and allocated tremendous resources in an attempt to incorporate the ideas and visions of sustainability into the reality of cities. As a result, the increased pressure on cities has led to a stronger need to build sustainable cities that last. Designing sustainable cities of the future, educated by the lessons of the past and anticipating the challenges of the future, entails articulating a multi-scalar vision and these key principles—energy, ecology, infrastructure, waste, water, livability, mobility, accessibility, economy, and culture—while responding to major societal trends and paradigm shifts in science and technology [10].

Sustainable cities have been the leading global paradigm of urbanism thanks to the models of sustainable urban form proposed as new frameworks for redesigning and restructuring urban places for making urban living more sustainable. Compact cities and eco-cities are the most advocated models of sustainable urbanism. It is argued that the compact city model is able to contribute to and support the balancing of the three goals of

sustainability (e.g., [20, 23, 31, 33, 34]), and that the eco-city model is able to achieve the key objectives of environmental sustainability and to produce some economic and social benefits of sustainability (e.g., [11, 17, 37–39, 55, 66]). While the environmental goals of sustainability dominate in the discourse of the eco-city (e.g., [5, 6, 32, 48, 51, 77]), the discourse of the compact city emphasizes the economic goals of sustainability (e.g., [31, 34]). As regards the social goals of sustainability, they are of less focus in the eco-city compared to the compact city (e.g., [6, 7]). However, emphasizing one of the dimensions of sustainability remains a shortcoming (failure to meet certain standards in plans) and deficiency (lacking some necessary elements) in the urban context. Therefore, it is of high relevance and importance to integrate the models of compact cities and eco-cities so as to consolidate and harness their design strategies and environmental technologies to deliver the best outcomes of sustainability within the framework of sustainable cities, or in accordance with the vision of urban ecology.

The change is still inspiring and the academic and practical endeavor continues to induce and motivate scholars, practitioners, and policymakers alike to enhance the existing models of sustainable cities, or to propose integrated models in response to new major global trends and paradigm shifts in science and technology. Indeed, sustainable cities are currently undergoing unprecedented transformative changes in light of the recent paradigm shift in science and technology brought on by big data science and analytics. These marked changes are motivated by the increased need to tackle the problematicity surrounding sustainable cities in terms of their development planning approaches, operational management mechanisms, and fragmentary design strategies and technology solutions related to compact cities and eco-cities, respectively [21]. They are also motivated by the quest for achieving the Sustainable Development Goal (SDG) 11 of the United Nations' 2030 Agenda—Sustainable Cities and Communities in terms of making cities sustainable, resilient, inclusive, and safe [74], which has increased the need to understand, plan, and manage sustainable cities in new and innovative ways. These are increasingly based on more advanced forms of ICT, especially big data technologies. The United Nations's 2030 Agenda regards advanced ICT as a means to promote socio-economic development, restore 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 [75]. This is associated with the multifaceted potential of smart cities with respect to the role of big data technologies and their novel applications in strategic sustainable urban development. The explosive growth of urban data, coupled with their analytical power, opens up for new opportunities for innovation in sustainable cities. Regardless, cities are increasingly being seen through big data [68].

Most of the problems, issues, and challenges related to sustainable cities largely relate to how this form of human settlement should be monitored, understood, analyzed, planned, designed, and managed in order to improve and advance sustainability. The underlying argument is that more innovative solutions and sophisticated methods are needed to address and overcome the kind of complexities and wicked problems inherently embodied in sustainable cities. This brings us to the question related to the weak connection between sustainable cities and smart cities and their extreme fragmentation as approaches and landscapes, respectively, both at the technical and policy levels, adding to their opposite conceptual characteristics and existing tensions (e.g., [1–3, 16, 45, 65, 70,78]). Therefore, there has been a conscious push for sustainable cities across the globe to be smarter and thus more sustainable by developing and implementing data-driven technology solutions so as to enhance their designs, strategies, and policies and thus optimize operational efficiency, strengthen infrastructure resilience, and improve social equity and life quality. This trend is evinced by numerous studies conducted recently on sustainable cities, especially eco-cities (e.g., [12–14, 21, 24–26, 30, 52, 58–61, 64, 67, 69, 71]). This is owing to the core enabling and driving technologies of the Internet of Things (IoT) and big data analytics offered by smart cities in relation to sustainability (e.g., [2, 4, 18, 19, 28, 49, 50, 53, 57, 72, 73, 79, 80]).

In light of the above, sustainable cities are increasingly embracing and leveraging what smart cities have to offer in terms of big data technologies and their novel applications in an attempt to effectively deal with the complexities they inherently embody and to efficiently monitor, evaluate, and improve their performance with respect to sustainability—under what has been termed “data-driven smart sustainable cities.” In fact, the real challenge for the future lies in moving genuinely past the assumption that there are only two contrasting, mutually exclusive realities—either sustainable cities or smart cities. An “either/or” approach will hamper progress towards urban sustainability, as the huge challenges facing sustainable cities within many of their administration spheres (transport, traffic, mobility, energy, environment, waste, healthcare, public safety, governance, etc.) require an integrated approach to urbanism.

The aim of this paper is to develop an applied theoretical framework for strategic sustainable urban development planning based on a case study analysis. This entails identifying and integrating the underlying components of data-driven smart sustainable cities of the future in terms of the dimensions, strategies, and solutions of the leading global paradigms of sustainable urbanism and smart urbanism. This work is based on the outcomes of four case studies, namely:

- (1) Compact cities [20];
- (2) Smart eco-cities [17];
- (3) Data-driven smart cities [18]; and
- (4) Environmentally data-driven smart sustainable cities [19].

The remainder of this paper is structured as follows: Section 2 focuses on the research methodology adopted in this study. Section 3 presents the results in terms of the four case studies and their findings, as well as the underlying components of data-driven smart sustainable cities of the future based on these results. Section 4 discusses and interprets the results in the perspective of previous studies. Section 5 develops, describes, and illustrates an applied theoretical framework for strategic sustainable urban development planning. This paper ends, in Section 6, with concluding remarks.

Research methodology

This study employs a case study approach to develop an applied theoretical framework for strategic sustainable urban development planning. The case study approach, which is described in more detail by Bibri [8, 9], was used first to illuminate the urban phenomena of compact cities, smart eco-cities, data-driven smart cities, and environmentally data-driven smart sustainable cities by examining and comparing two cases within each of these analytical frameworks from a total of six of the ecologically and technologically leading cities in Europe. Generally, the case study is a descriptive qualitative approach that is used as a tool to study specific characteristics of a complex phenomenon. This approach involves describing, analyzing, and interpreting that phenomena. This pertains, in this context, to the prevailing conditions related to plans, projects, and achievements, specifically, how the six cities selected behave as to what has been realized, the ongoing implementation of plans, and the execution of urban projects. This is based on the corresponding practices and strategies for sustainable development and technological development. To obtain a detailed form of knowledge in this regard, a five-step process tailored to each of the four case studies was adopted (Table 1).

Table 1 A five-step process tailored to each of the four case studies conducted**Compact cities**

- Using a narrative framework that focuses on the compact city model and its contribution to the three goals of sustainability as a real-world problem and that provides essential facts about it, including relevant background information
- Introducing the reader to key concepts, strategies, practices, and policies relevant to the problem under investigation
- Discussing benefits, conflicts, and contentions relevant to the problem under investigation
- Explaining the actual solutions in terms of plans, the processes of implementing them, and the expected outcomes.
- Offering an analysis and evaluation of the chosen solutions and related issues, including strengths, weaknesses, tradeoffs, and lessons learned.

Eco-cities

- Using a narrative framework that focuses on the eco-city as a real-world problem and provides essential facts about it, including relevant background information
- Introducing the reader to key concepts, models, and design strategies relevant to the problem under investigation
- Discussing benefits and research gaps and issues relevant to the problem under investigation
- Explaining the actual solutions in terms of plans, the processes of implementing them, and the expected outcomes
- Offering an analysis and evaluation of the chosen solutions and related issues, including strengths, weaknesses, tradeoffs, and lessons learned.

Data-driven smart cities

- Using a narrative framework that focuses on the data-driven smart city as a real-world problem and provides essential facts about it, including relevant background information
- Introducing the reader to key concepts, technologies, and data-driven smart sustainable urbanism processes and practices relevant to the problem under investigation
- Providing an overview of the literature review previously conducted in relation to the study, which delivers a comprehensive, state-of-the-art review on the sustainability and unsustainability of smart cities in relation to big data technologies, analytics, and application in terms of the underlying foundations and assumptions, research problems and debates, opportunities and benefits, technological developments, emerging trends, future practices, and challenges and open issues
- Explaining the actual solutions in terms of plans, the processes of implementing them, and the expected outcomes
- Offering an analysis and evaluation of the chosen solutions and related issues, including strengths, weaknesses, tradeoffs, and lessons learned.

Environmentally data-driven smart sustainable cities

- Using a narrative framework that focuses on data-driven smart solutions and their role and potential in improving and advancing environmental sustainability in the framework of the smart sustainable city as a real-world problem, and provides essential facts about it, including relevant background information.
- Introducing the reader to key concepts, core enabling technologies, infrastructures, landscapes, frameworks, as well as urban operating systems and urban operations centers, all with relevance to the problem under study.
- Identifying the commonalities and differences between the two cities with respect to the emerging technologies
- Explaining the actual solutions in terms of plans and visions, the processes of implementing them, and the realized and expected outcomes
- Offering an analysis and evaluation of the relevant solutions and related issues, including strengths, weaknesses, and lessons learned.

The objective of the four case studies carried out on contemporary real-world phenomena is to inform the theory and practice of data-driven smart sustainable cities of the future as an integrated and holistic paradigm of urbanism by illustrating what has worked well, what needs to be improved, and how this can be done in the era of big data and in the face of urbanization. These case studies are particularly useful for illustrating the general principles underlying these phenomena, for understanding how different elements fit together and (co-)produce the observed impacts in a particular urban context based on a set of intertwined factors in the context of these phenomena, as well as for generating new ideas about and research questions regarding the relationships between these phenomena.

Results**The case studies and their findings**

This section presents the results of case study research carried out on the prevailing models of sustainable urbanism and the emerging models of smart urbanism, as well as a tabulated version of the dimensions, strategies, and solutions of these models based on those results. The empirical phase of the future study involves conducting four case studies. This investigation is done within the frameworks of compact cities (Gothenburg and Helsingborg), smart eco-cities (Stockholm and Malmö), data-driven smart cities (London and Barcelona), and environmentally data-driven smart sustainable cities (Stockholm and Barcelona).

As to the first case study, it investigates how the compact city model is practiced and justified in urban planning and development with respect to the three dimensions of sustainability, and whether any progress has been made in this regard. Specifically, it focuses on the prevalent design strategies of the compact city model, the ways in which they mutually complement and beneficially affect one another in terms of producing the expected benefits of sustainability, as well as the extent to which the compact city model supports the balancing of the three goals of sustainability. This study demonstrated that compactness, density, diversity, mixed land use, sustainable transportation, and green space are the core design strategies of compact city planning and development, with the latter being contextually linked to the concept of green structure, an institutional setup under which the two investigated cities operate. It also revealed a clear synergy between the underlying design strategies in terms of their cooperation to produce combined effects greater than the sum of their separate effects with respect to the benefits of sustainability as to its tripartite composition. Indeed, the compact city model as practiced by the two cities is justified by its ability to contribute to the economic, environmental,

and social goals of sustainability. However, the study indicated that the environmental and social goals still play second fiddle, and that new measures are being implemented to strengthen the influence of these goals in urban planning and development practices. In this context, it is particularly noticeable that compact urbanism is being enhanced with some elements of eco-urbanism and strengthened by new institutionalized practices accordingly to support the balancing of the three dimensions of sustainability.

Regarding the second case study, it investigates how the eco-city model, especially its three sustainability dimensions, is practiced and justified in urban planning and development at the local level. Specifically, it focuses on the core strategies and solutions of the eco-city district model, the way in which they mutually complement one another in terms of producing the expected benefits of sustainability, as well as the extent to which the eco-city district model supports the integration of the three goals of sustainability. This study showed that the eco-city district model involves mainly design and technology as the core strategies and solutions for achieving urban sustainability, in addition to behavioral change. Design encompasses greening, passive solar houses, sustainable transportation, mixed land use, and diversity. Technology comprises green energy systems, energy efficiency systems, and sustainable waste management systems. Design contributes to the three goals of sustainability, and technology contributes mostly to the environmental and economic goals of sustainability. Behavioral change is associated with sustainable travel, waste separation, and energy consumption. Moreover, at the core of the eco-city district model is the clear synergy between the core underlying strategies and solutions in terms of their cooperation to produce combined effects greater than the sum of their separate effects with respect to the benefits of sustainability, yet with its environmental dimension clearly dominating over its economic and social dimensions. This is due to the fact that the eco-city emphasizes ecological design, ecological diversity, and passive solar design, as well as environmental management and other key environmentally sound policies. Thus, the environmental goals remain at the core of planning, while the economic and social goals still play second fiddle in eco-city development. Nevertheless, it was observed that new measures are being implemented to strengthen the influence of these goals over urban planning and development practices, but mainly in one of the two investigated cases. Regardless, the social goals remain of less focus compared to the economic goals.

Concerning the third case study, it investigates how the emerging data-driven smart city is practiced and justified in terms of the development and implementation of its innovative technologies and solutions for sustainability. This study showed that this emerging paradigm

of urbanism has a high level of the development of applied data-driven technologies as well as their implementation in different urban domains in order to optimize and enhance their performance in relation to the different aspects of sustainability. The high level of the development of data-driven technologies (notably ICT infrastructure and data sources) is associated with the degree of the readiness of the city administration to introduce data-driven technologies in operational management and development planning. The high level of the implementation of data-driven technologies is associated with the degree of the adoption of applied data-driven solutions in the different spheres of the city administration, including transport, traffic, energy, environment, citizen participation, public safety, and healthcare. In this respect, a number of technical and institutional competences are employed and established to improve and advance sustainability, notably horizontal information platforms, operations centers, dashboards, educational institutes and training programs, innovation labs, research centers, and strategic planning and policy offices. The outcome of this study demonstrates the untapped synergistic potential of the integration of innovative solutions and sustainable strategies on the basis of the IoT and big data technologies.

As regards the fourth case study, it investigates the potential and role of data-driven smart solutions in improving and advancing environmental sustainability in the context of smart cities as well as sustainable cities, under what can be labeled “environmentally data-driven smart sustainable cities.” It also provides an overview of the technical literature on the IoT and big data technologies within the framework of smart sustainable cities. This study corroborated that smart grids, smart meters, smart buildings, smart environmental monitoring, and smart urban metabolism are the main data-driven solutions applied for improving and advancing environmental sustainability in eco-cities and smart cities combined. There is a clear synergy between these solutions in terms of their cooperation to produce combined effects greater than the sum of their separate effects—with regard to the environment. It was concluded that city governments do not have a unified agenda as a form of strategic planning, and data-driven decisions are unique to each city, so are environmental challenges. Big data are the answer, but each city sets its own questions based on what characterizes it in terms of visions, policies, strategies, pathways, goals, and priorities.

The primary intention of examining and comparing the two emerging paradigms of smart urbanism (data-driven smart cities) and sustainable urbanism (environmentally data-driven smart sustainable cities) is to combine what they have as strengths, harness their clear synergies, and offer an opportunity for both city models to learn from each other with respect to data-driven

smart technologies and green technologies, respectively, for reaching key targets of environmental sustainability. The rationale for conducting the fourth case study is to elaborate further on the relationship between emerging data-driven technology solutions and environmental sustainability in connection with energy efficiency, pollution reduction, and urban metabolism. This is because the focus of the second case study is, by design approach, on the core environmental dimension of sustainability with reference to renewable energy systems, waste management systems, green and blue infrastructure, and passive solar design. Concerning the focus of the third case study, it is similarly on data-driven technologies and data-oriented competences used for developing and implementing applied innovative solutions in relation to all three dimensions of sustainability.

The underlying components of data-driven smart sustainable cities of the future

Compact city dimensions and strategies

The compact city is the most advocated model of sustainable urbanism due to its ability to produce the benefits of sustainability as to its tripartite composition,

though to varying degrees. When strategically planned and well-designed, the compact city becomes able to support the balancing of the three goals of sustainability. In other words, the compact city model can offer environmentally sound, socially beneficial, and economically viable development through highly dense and multidimensional mixed use patterns that rely on sustainable transportation and favor green open space (Table 2). As such, it can be viewed as an all-encompassing understanding of urban complexities as well as an all-embracing conception of planning practices and strategies for achieving urban sustainability.

Eco-city dimensions, strategies, and technologies

The eco-city model delivers positive outcomes in terms of providing healthy and livable human environments in conjunction with minimal demand on resources and minimal impact on the environment. It emphasizes green design strategies and environmental technology solutions, supported by behavioral change, for achieving urban sustainability. The image of the eco-city has proven to be a highly influential translation of what a sustainable city should be, especially if, according to

Table 2 The design criteria and strategies of the compact city for achieving the goals of sustainability

Design criteria	Strategies for environmental, economic, and social sustainability
Compactness	<ul style="list-style-type: none"> • Build and develop centrally • Concentrate around strategic nodes • Complement and mix • Reserve outer city areas for future development
Density	<ul style="list-style-type: none"> • High density of built objects in designed and emergent compact urban form • Diverse scales of built objects • Distribution of building footprints with frequent larger buildings • Greater density in strategic nodes • Prioritized density close to the central points of strategic nodes • High-density hand in hand with multidimensional mixed land use
Mixed land use	<ul style="list-style-type: none"> • Physical land use mix (horizontal/spread of facilities, vertical mix of uses, amenity, public space, etc.) • Economic mix (business activity, production, consumption, etc.) • Social mix (housing, demography, lifestyles, visitors, etc.) • Greater mix of housing, business, and facilities in strategic nodes • Multidimensional mixed land use hand in hand with sustainable transportation
Sustainable transportation	<ul style="list-style-type: none"> • Cycling and walking • Public transport (metro, buses, tram, etc.) • Mobility management • Increased accessibility through public transport infrastructure improvements • Sustainable transportation hand in hand with multidimensional mixed land use and high density • Network structure of link areas to connect the major nodes of the transport system • Separate lanes for the public transport for faster journey time and a punctual and reliable system • More services along the main corridors for greater frequency • An easy to understand, safe, and secure system for guaranteeing quality and service • Multi-model traveling in strategic nodes to support their dense and diverse central points
Green structure	<ul style="list-style-type: none"> • Green areas and parks • Green areas hand in hand with density • Protection and integration of natural, agricultural, and cultural areas through intensification
Intensification	<ul style="list-style-type: none"> • Increase in population • Increase in redevelopment of previously developed sites, subdivisions and conversions, and additions and extensions • Increase in development of previously undeveloped urban land • Increase in density and diversity of sub-centers • Investment in and improvement of transport infrastructure and services

Table 3 The key strategies and solutions of the eco-city district for achieving the three goals of sustainability

Design and technology criteria	Strategies and solutions for environmental, economic, and social sustainability
Environmental sustainability	
Sustainable energy systems	<ul style="list-style-type: none"> • 100% locally generated renewable energy—sun, wind, and water • Local production of electricity—solar energy • Passive, low-energy, and net-zero buildings/houses • Bio-fueled CHP system
Sustainable waste management	<ul style="list-style-type: none"> • Convenient and smart waste collecting system • Vacuum waste chutes • Food waste disposers • Wastewater and sewage treatment system • Biological waste separation procedures • Biogas digesters • Behavioral change
Sustainable materials	<ul style="list-style-type: none"> • High performance materials • Resource-efficient (recycled and reused) materials • Minimized building waste • Pollution prevention
Sustainable transportation	<ul style="list-style-type: none"> • Cycling and walking • Public transport (metro, buses, tram, etc.) • Car pools (biogas and electric) • Private cars (biogas and electric) • Mobility management • Smart transport management • Smart traffic management • Behavioral change
Green and blue infrastructure	<ul style="list-style-type: none"> • Greening • Rainwater harvesting • Ecological diversity • Biodiversity • Green factor supplemented with green points • Green parks • Green streets and alleys • Green roofs • Rain gardens • Bioswales • Permeable pavements
Economic Sustainability	
Multidimensional mixed uses	<ul style="list-style-type: none"> • Physical land use mix (vertical and horizontal, amenities, facilities, public spaces, etc.) • Economic mix (business activity, production, consumption, etc.) • Some aspects of social mix (housing, demography, lifestyles, visitors, etc.)
Economic growth and business development	<ul style="list-style-type: none"> • Green-tech innovation • Green-tech production and export • R&D activities • Entrepreneurial and innovation-based startups • Industrial and technological investment • Job creation and skill development • Government, industry, and academia collaboration • International cooperation
Social sustainability	
Equity	<ul style="list-style-type: none"> • Equal access to basic services • Reduction of socio-spatial segregation • Flexible design of housing in terms of tenures and forms • Affordable housing for all by means of efficient, careful processes
Life quality	<ul style="list-style-type: none"> • Material living conditions • Employment • Meeting places for social interaction • Ready access to facilities and public spaces • Recreation and leisure time • Natural surveillance • Security and safety of individuals and their living environment • Physical and mental health • Quality education • Social belonging and cohesion

Table 3 The key strategies and solutions of the eco-city district for achieving the three goals of sustainability (*Continued*)

Design and technology criteria	Strategies and solutions for environmental, economic, and social sustainability
Citizen participation	<ul style="list-style-type: none"> • Housing design enabling residents to remain throughout all stages of life • Citizen involvement and consultation as to decision-making • Citizenship plurality consolidation • Citizen empowerment for community engagement and co-creation

Roseland [56], planned and designed following the 10 principles of Urban Ecology [56]. This relates to what is called sustainable integrated cities or districts (see [11] for a detailed review). Table 3 presents the key design strategies and technology solutions of the eco-city in accordance with the three dimensions of sustainability.

Data-driven smart city dimensions and solutions

The phenomenon of the data-driven smart city has materialized as a result of the emerging paradigm of big data science and analytics and the wider adoption of the underlying technologies. This emerging paradigm of urbanism emphasizes the intensive datafication of the built environment and implements the datafication tools for optimizing and enhancing urban operations, functions, services, strategies, designs, and policies in ways that improve sustainability, efficiency, equity, and the quality of life. Datafication represents an urban trend which defines the key to the core functioning of the city through a reliance on big data analytics and its core enabling and driving technologies in terms of their use in supporting decision-making processes pertaining to a wide range of practical uses and applications within various urban systems and domains. The data-driven smart city is characterized by the ability of city management agencies and city policy and planning offices to use advanced technologies for data generation, processing, and analysis aimed at the adoption of solutions for enhancing the living standards of citizens thanks to the development of social, economic, and ecological areas of the urban environment (Table 4).

Data-driven smart city solutions and strategies

The environmentally data-driven smart sustainable city is seen as an experimental city for testing and introducing new technological solutions for implementing reforms in order to make progress towards achieving the goals of environmental sustainability. These solutions play a significant role in monitoring, evaluating, and improving the environmental performance of both eco-cities and smart cities, with insights into how to integrate these approaches to urban development on the basis of the IoT and big data technologies by pursuing a number of strategies (Table 5). The environmentally data-driven smart sustainable city is characterized by the ability to use these advanced technologies to generate,

process, analyze, and harness urban data for the purpose of extracting deeper insights that can be used and leveraged to make well-informed decisions to address the existing and new problems and challenges related to environmental sustainability. These data-driven solutions can be adopted by city management agencies and city planning and policy offices to enhance the performance of urban systems and domains with regard to the environment.

An applied theoretical framework for strategic sustainable urban development planning

The identified core dimensions, strategies, and solutions of the prevailing paradigms of sustainable urbanism and the emerging paradigms of smart urbanism are integrated into an applied theoretical framework for strategic sustainable urban development planning (Fig. 1). Accordingly, this integrated framework is derived based on the outcome of case study research. It illustrates the combination and integration of the underlying components of the data-driven smart sustainable city of the future. In this respect, there are four basic categories and criteria that are used in defining the data-driven smart sustainable city of the future: (1) compact urban design strategies at the top left-hand corner; (2) eco-city design strategies and technology solutions at the top-right hand corner; (3) data-driven smart city technologies, competences, and solutions for sustainability at the bottom left-hand corner; and (4) environmentally data-driven smart sustainable city solutions and strategies at the bottom right-hand corner.

The proposed framework is of an applied theoretical nature because it represents an integration and fusion of a number of theories from different established and emerging city-related academic and scientific disciplines together with the effects of their application to the built environment. These theories and disciplines (see Bibri [15] for an interdisciplinary and transdisciplinary framework) have high application potential in terms of informing and guiding the processes and practices of the future model of urbanism. This relates to the core foundational concepts and principles of data-driven smart sustainable urbanism as an applied domain in terms of its scientific, technological, computational, social, cultural, and political facets. In short, the underlying theories constitute a foundation for actions as illustrated through case studies. Besides, this study needs to link to what is happening in the world around us as regards

Table 4 The key dimensions and solutions of the data-driven smart city for achieving sustainability

Technologies and competences	Solutions for environmental, economic, and social sustainability
ICT infrastructure	<ul style="list-style-type: none"> • Availability and number of the city Wi-Fi access points • Share of households with Internet access • Coverage of citizens with the mobile batch communication • Degree of penetration of the fiber-optic network • Number of Wi-Fi hotspots in the private and corporate segments • Connection speed of the fixed broadband in the private segments • Network capacity
Data sources	<p>Open data and electronic payments</p> <ul style="list-style-type: none"> • Data openness and presence of public authorities in the web • Number of datasets available on the portals of open data • Electronic and mobile payments <p>Citizens</p> <ul style="list-style-type: none"> • Degree of Internet penetration • Degree of mobile penetration • Proportion of smartphone owners • Proportion of PC and laptop owners • Broadband Internet subscription in the private sector • Number of visitors of municipal services web-portal <p>The IoT-sensor devices</p> <ul style="list-style-type: none"> • Road traffic • Public transport • Cycling • Parking • Street lighting • Electricity grids • Buildings • Waste removal and disposal • Water • Air and noise • Density of CCTV cameras
Applications for sustainability	<ul style="list-style-type: none"> • Transport management • Traffic management • Street lighting management • Mobility management • Waste management • Energy management • Environmental control and monitoring • Buildings management • Public safety • Healthcare • Citizen participation • Planning and design
Technical and institutional competences	<ul style="list-style-type: none"> • Horizontal information systems • Operations centers and dashboards • Research centers and innovation labs • Educational centers and training programs • Strategic planning and policy offices

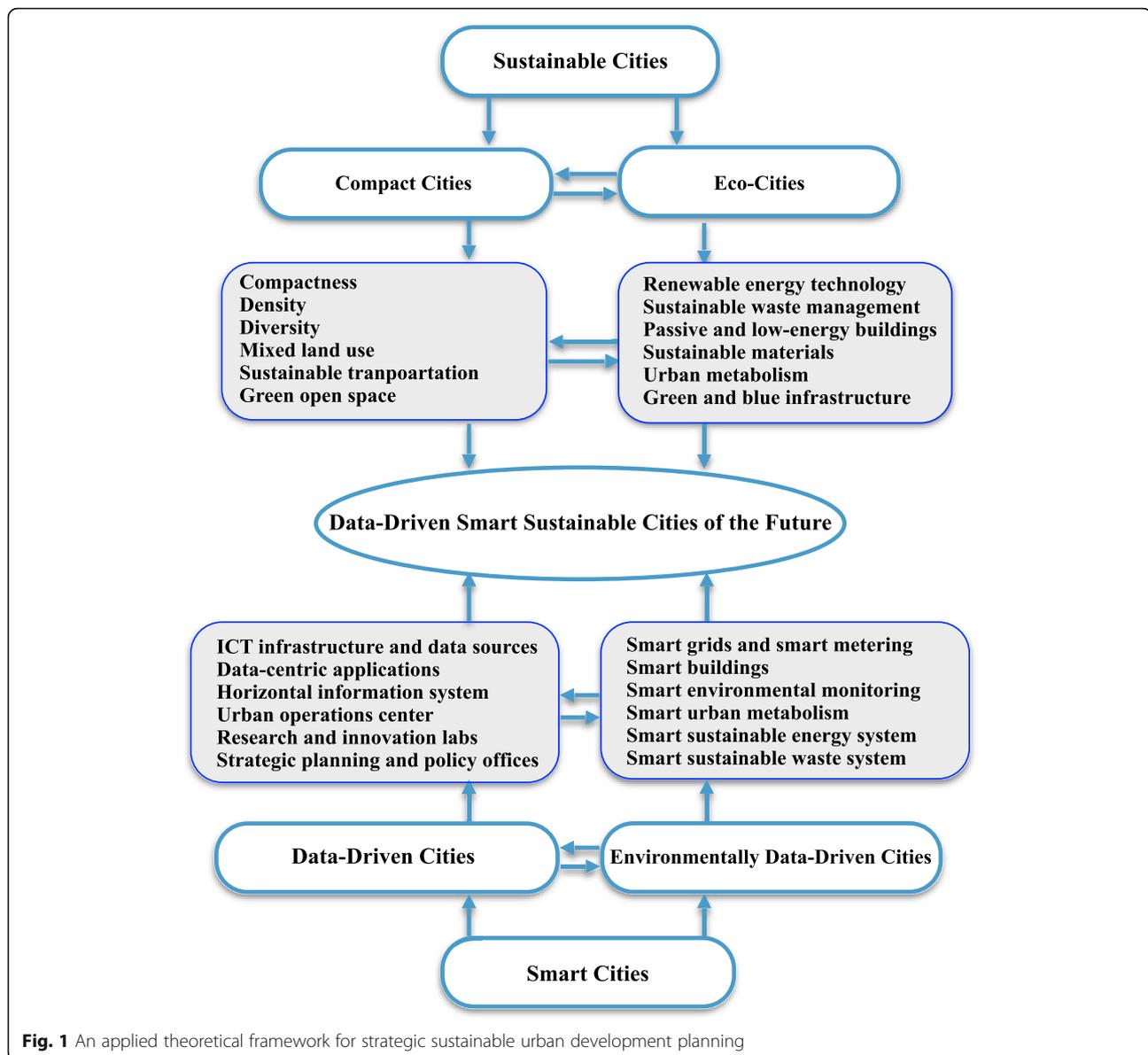
successful practices, knowledge advancement, scientific paradigm shifts, and technological innovations.

Discussion

The focus of the six cases investigated is on the nature and extent of the contribution of the four identified models of urbanism to the goals of sustainability. This involves integrating and balancing the three dimensions of sustainability with respect to sustainable cities and highlighting the enabling role and innovative potential of data-driven technologies and solutions pertaining to smart cities in improving and advancing sustainability. This is coupled with how each model of urbanism

Table 5 The key solutions and strategies of the environmentally data-driven smart city

Solutions and strategies
Smart grids and smart metering
Smart buildings
Smart environmental monitoring
Smart urban metabolism
Smart sustainable energy system
Smart sustainable waste system



relates to another in the context of sustainability. Up till now, the four models of sustainable urbanism and smart urbanism investigated are weakly connected as approaches and extremely fragmented as landscapes, both at the technical and policy levels. The compact city and eco-city models of sustainable urbanism, which have been around for over four decades or so, have many overlaps among them in their ideas, concepts, and visions, as well as distinctive concepts and key differences. The overlap is justified by the fact that they both represent the central paradigms of sustainable urbanism, and so, they are, to a great extent, compatible and not mutually exclusive. As a result, a recent wave of research has started to focus on improving the performance of the

compact city and the eco-city by partly or completely integrating their design strategies and technology solutions (e.g., [20–22, 29, 31, 38]). This is at the core of the mission of urban ecology as to creating compact eco-cities based on a number of principles that are intended to achieve the goals of sustainability [56]. The emerging Eco-Compact or Eco-Density initiatives, for example, are seen as an unprecedented planning effort and a response to the deconcentration of land use due to urban sprawl. Accordingly, these initiatives use density, mixed-land use, and sustainable transportation as catalysts towards livability, affordability, and environmental sustainability. They aim to deliver more efficient land use, improve green energy systems, and build resilient and adaptable

urban communities. Recent research within eco-urbanism tends to focus on the three dimensions of sustainability in terms of benefits and shortcomings (e.g., [11, 32, 40, 54]). This pertains to the integrated models for urban development, which explore the development of SIDs as a model for high-density, high-liveability future cities [10–12]. In recent years, the development of sustainable urban districts, especially eco-city districts, has attracted increased interest and become an expansion route for many growing cities (e.g., [36, 47, 51]) as well as a common way to address and implement sustainability in the built environment [36, 62]. However, the development of new sustainable urban districts is often subject to more rigorous sustainability objectives with respect to their evaluation in order to meet future challenges [51].

The focus of the six cases investigated is on the nature and extent of the contribution of the four identified models of urbanism to the goals of sustainability. This involves integrating and balancing the three dimensions of sustainability with respect to sustainable cities and highlighting the enabling role and innovative potential of data-driven technologies and solutions pertaining to smart cities in improving and advancing sustainability. This is coupled with how each model of urbanism relates to another in the context of sustainability. Up till now, the four models of sustainable urbanism and smart urbanism investigated are weakly connected as approaches and extremely fragmented as landscapes, both at the technical and policy levels. The compact city and eco-city models of sustainable urbanism, which have been around for over four decades or so, have many overlaps among them in their ideas, concepts, and visions, as well as distinctive concepts and key differences. The overlap is justified by the fact that they both represent the central paradigms of sustainable urbanism, and so, they are, to a great extent, compatible and not mutually exclusive. As a result, a recent wave of research has started to focus on improving the performance of the compact city and the eco-city by partly or completely integrating their design strategies and technology solutions (e.g., [20, 21, 29, 31, 38]). This is at the core of the mission of urban ecology as to creating compact eco-cities based on a number of principles that are intended to achieve the goals of sustainability [56]. The emerging Eco-Compact or Eco-Density initiatives, for example, are seen as an unprecedented planning effort and a response to the deconcentration of land use due to urban sprawl. Accordingly, these initiatives use density, mixed-land use, and sustainable transportation as catalysts towards livability, affordability, and environmental sustainability. They aim to deliver more efficient land use, improve green energy systems, and build resilient and adaptable urban communities. Recent research within eco-

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The data-driven smart city model shares the challenges of sustainable development with the two models of sustainable urbanism, with the main difference being that it focuses on the use and adoption of data-driven technologies and solutions and related technical and institutional competences to overcome these challenges—rather than on the planning practices and design strategies of urban sustainability. The phenomenon of the data-driven city has materialized as a result of the emergence of big data science and analytics and the wider adoption of the underlying technologies, the vast deployment of the IoT, the explosive growth of urban data, and the transformation of the urban landscape in the light of urbanization [10]. This emerging paradigm of urbanism is too often associated with “smarterness” under what is labeled “data-driven smart cities” (e.g., [18, 27, 44]), particularly in relation to efficiency, sustainability, resilience, equity, and the quality of life.

Concerning the environmentally data-driven smart sustainable city model, it emphasizes the dimension of environmental sustainability and employs data-driven technology solutions to reach environmental targets. In this sense, this model combines concepts and ideas from both the eco-city and the data-driven smart city. These two models are increasingly being merged together in a bid to overcome the significant challenges posed by climate change in the face of the escalating trend of urbanization. The eco-city across the globe is increasingly embracing and leveraging what the smart city has to offer in terms of advanced ICT, especially the IoT and big data technologies, in an effort to monitor, evaluate, and improve its performance with respect to sustainability, especially its environmental and economic dimensions (e.g., [11, 24, 25, 35, 64, 67])—under what has been termed “smart eco-cities” or “data-driven smart eco-cities.” It has become increasingly feasible to attain important improvements of sustainability by integrating eco-urbanism and smart urbanism thanks to the proven role and untapped potential of data-driven technologies

[12, 13] While both of these approaches to urban development implement data-driven technology solutions to improve and advance environmental sustainability, they remain significantly divergent with respect to their priorities, visions, policies, strategies, pathways, and goals, thereby the meaningfulness of their integration in the fourth case study.

All in all, the compact city and eco-city strategies and their integration have recently been enhanced and strengthened through new planning and development practices, and are increasingly being supported and leveraged by the applied technology solutions offered by data-driven smart cities, especially within the ecologically advanced nations or those countries known for their highest level of sustainable development practices. The ultimate aim is to develop and implement more effective approaches to the balanced integration of the three dimensions of sustainability, and to produce combined effects of the strategies and solutions pertaining to the prevailing and emerging paradigms of urbanism that are greater than the sum of their separate effects with respect to the benefits of sustainability.

It must be noted that there currently are neither real examples of a truly data-driven smart sustainable city that have actually been presented to the world, nor a future proofing of the IoT and big data technologies to ensure that these can be adapted, modified, and built upon in a more effective way in the medium term. Therefore, the data-driven technology solutions yet to be diffused must be evaluated through an actual implementation and related expected positive outcomes in order to determine their actual opportunities for improving and advancing sustainability. The road ahead promises to be exciting as more cities become aware of the clear prospect of integrating sustainable urbanism and smart urbanism—for meaningful uses and collective advantages. However, it is too early to predict the full scale of the negative consequences and hidden pitfalls associated with smart urbanism (e.g., [41–43, 45, 46, 63, 76]), including technocratic reductionism, technocentricity, city governance corporatization, dataveillance and geo-surveillance, privacy encroachment, and mind control and manipulation.

Conclusion

Sustainable cities are always about citizens. Being data-driven smart about sustainable cities requires to connect directly to the concerns and aspirations of people with respect to environmental protection, economic regeneration, and social justice. People have always aspired or preferred to live in sustainable cities to improve their lives. Smart urbanism is being embraced anew as a strategic move to contribute to sustainable cities that make urban living more sustainable over the long run.

Towards this end, sustainable cities have to learn faster and identify strategies and pathways that work to attain this vision. Therefore, it is scholarly worthy to venture some thoughts about where it might be useful to channel the efforts now and in the future in what has been termed as data-driven smart sustainable cities. Big data technologies are certainly enriching our experiences of how cities function. They are offering many new opportunities for enhancing decision-making with respect to our knowledge of how to monitor, understand, analyze, and plan cities to improve sustainability, efficiency, resilience, equity, and the quality of life. However, whether these developments will be to our collective advantage or disadvantage is yet to be seen for there is undoubtedly a dark side to all technological developments.

The aim of this paper was to develop an applied theoretical framework for strategic sustainable urban development planning based on a case study analysis. We identified, distilled, and enumerated the underlying components of data-driven smart sustainable cities of the future in terms of the dimensions, strategies, and solutions of the leading global paradigms of sustainable urbanism and smart urbanism. Subsequently, we combined and integrated these components into a framework for strategic sustainable urban development planning. The argument underlying the essential elements of the integrated framework is that the IoT and big data technologies and their novel applications being offered by smart cities of the future have great potential to enhance and consolidate the design strategies and environmental technology solutions of sustainable cities. Besides, the field of sustainable urbanism needs to extend its boundaries and to broaden its horizons beyond the compactness of the built form, green design, and environmental technology characterizing sustainable cities to include technological innovation opportunities by unlocking and exploiting the potential of emerging and future ICT. However, while advanced technologies can bring numerous advantages to sustainable urbanism, it is important to acknowledge the fact that these technologies can be problematic, and therefore, policy-makers and planners should be careful when employing them and placing huge expectations on their advancements.

The novelty of the proposed framework lies in integrating compact urban design strategies, eco-city design strategies and technology solutions; data-driven smart city technologies, competences, and solutions for sustainability; and environmentally data-driven smart sustainable city solutions and strategies. These combined have great potential to improve and advance the contribution of sustainable cities to the goals of sustainability through harnessing its synergistic effects and balancing the integration of its dimensions. In other words, the data-driven technologies and solutions offered by smart

cities as an approach to urban development are to be applied in the operational management and development planning of sustainable cities in ways that enable them to continuously make and monitor their progress towards achieving the goals of sustainability.

Abbreviations

ICT: Information and Communication Technology; IoT: Internet of Things; SDG: Sustainable Development Goal; SIDs: Sustainable Integrated Districts

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