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Review

Future City, Digital Twinning and the Urban Realm: A Systematic Literature Review

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Abstract: Digitalisation and the future city paradigm are becoming a trend in recent research and practices. Literature discusses digitalisation and its applications as the main gear in the transformation to the ideal future city vision. Yet, the concept of digitalisation is articulated in many interpretations and presented in different applications in the built environment. One emerging application is digital twinning. Literature envisions the potential of digital twinning applications in the urban realm and discusses the cognitive city model and its implications on the future of our cities, its urban realm and the built environment in general. With the evolving themes on the ideal future city model, this systematic review tackles the following questions: what are the key motives and drivers of the future city paradigm; what is a city digital twin; and what are their expected applications. Additionally, how literature envisions the definition of the city users and their experience in the urban realm of the city of the future. This review article explores related literature on the themes of future city model, digital urban realm, digital twinning and city users. The main findings are: identifying key gears of the future city model in literature, exploring city digital twin conceptualization and applications and discussing concepts on the definition of city user and user experience in the city of the future.

Keywords: future city; urban realm; digital twinning; city users

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1. Introduction

As the world population rapidly increases and cities expand, many questions stand to envision the future of our cities, its urban realm and the built environment. In the last few decades, research has depicted a broad spectrum of themes that touch on concerns on the future of cities and the urban realm with ongoing and evolving challenges such as city expansion, climate change and population growth. One distinct theme that attracts the concerns, particularly in developed countries, is the future of the city user in the urban realm of the future city [1,2]. Governmental and non-governmental efforts, along with recent and evolving research directions, are calling for rethinking the future of the city user in the city of the future, highlighting the ongoing changes in the city as a system, its urban realm and the built environment [3–5].

The 21st century imparted novel advances in technologies changing the way we think, perceive and interact with our cities, the urban realm and the built environment [6]. Digitalisation is one of the major advances of the 21st century that emerged and developed with the advancement of the information, communication and technology (ICT) industry [6,7]. In the context of the built environment, the concept of digitalisation is depicted as the restructuring of the physical setting of a physical environment into a digital, intangible and virtual environment [8–10]. The principles of digitalisation are built around the transformation of the physical built environment into an interactive, responsive and interconnected digital system that is accessed, monitored and facilitated virtually. This system is anticipated to enable novel dimensions on learning and analysing the events and conditions of the physical setting, and accordingly, contributes to enhancing the quality and performance of the physical built environment [11–13].

As described by Kevin Lynch [14], the built environment is formed by principle elements that shape the complete image of the city. On the city scale, buildings are rooms, pathways are corridors and the urban space is the living area. All of the city elements together form the image of the urban realm [14–16]. And the urban realm is the physical setting where city users live, interact and navigate dynamically [15,16]. Digitalisation and the revolution in technology applications, such as digital twin technology, are enabling new dimensions on reimagining the experience of city user in the city of the future [17]. The emerging of such dimensions raises questions on the future of the place we live in, interact with and navigate through, and necessitates the need to discover recent research, applications and visions on the themes of the digital urban realm, digital twin technology and city users in the city of the future. Accordingly, this article conducts a systematic review of recent literature to envision the key trends and perspectives of the future city. The study addresses the following research questions: What are future cities' motives and key drivers? What are the foreseen applications of digital twinning technology in the urban realm of the future city? And what is the foreseen definition of the user experience within the urban realm of the future city?

2. The Urban Realm in the Digital Era

One of the main drivers to understand the future city paradigm is the concept of the digital city. The concept of "Digital City" emerged in the early 21st century due to the revolution in the ICT industry that revealed many opportunities for thinking beyond the possible [18]. The concept started to thrive in related research, presenting a novel perspective for the future of our cities [18–20]. Nevertheless, no consensus has yet been reached around the definition of digital city among scholars. Some studies refer to the concept as the creation of an interconnected and virtual city infrastructure [21], and others refer to the concept as the development of a collective city data capital [22]. In contrast, others express the concept as the stabilizing of a healthier, environment-friendly and climate-resilient city [23]. In general, the digital city concept could be conceived as an umbrella for achieving interdisciplinary objectives, such as smart living, innovative economy and smart infrastructures [20,24,25].

The change in the way we perceive and interact with our city, the urban realm and the built environment has evolved with the development of the digital city conceptualisation and through the thriving of digitalisation applications [26,27]. According to studies [26,28], with digital twin technology, the physical settings of the actual city are mirrored in a digital environment. The parallel environment, so called "the digital replica", links the elements of the city together in a virtual, readable and measurable system [18,28]. With ICT applications, the digital replica can learn, analyse and react to the conditions of the actual city with informed decisions and recommendations that have the potential to improve the actual conditions of the city. In this scene, the city gains a dynamic character and the way we perceive and interact with the city could change accordingly [18,28].

In order to differentiate between the digital city model and the regular city model, research classifies the city in three main models: regular city, smart city and cognitive city [20,29,30]. In a regular city, city elements are disconnected digitally, and the city fabric is static and non-responsive to changes or interactions [20]. In a smart city, city elements are connected digitally, where a limited manner of interaction occurs between the city components together and between the city and its users. In a smart city model, the digital presentation of the city can learn, measure and document the conditions of the physical settings; however, interaction with the city user is limited to preliminary applications such as sensing and recording [29]. In a cognitive city, city elements are linked digitally in real-time and could learn, adapt and respond to interactions [30]. Research describes the cognitive city model as the collective intelligence of the city, where city fabric acts in a proactive manner to address ongoing changes and interactions between the city components together and between the city and its users, based on an interconnected grid of city elements represented in a collective digital system, as demonstrated in Figure 1 [29,30].

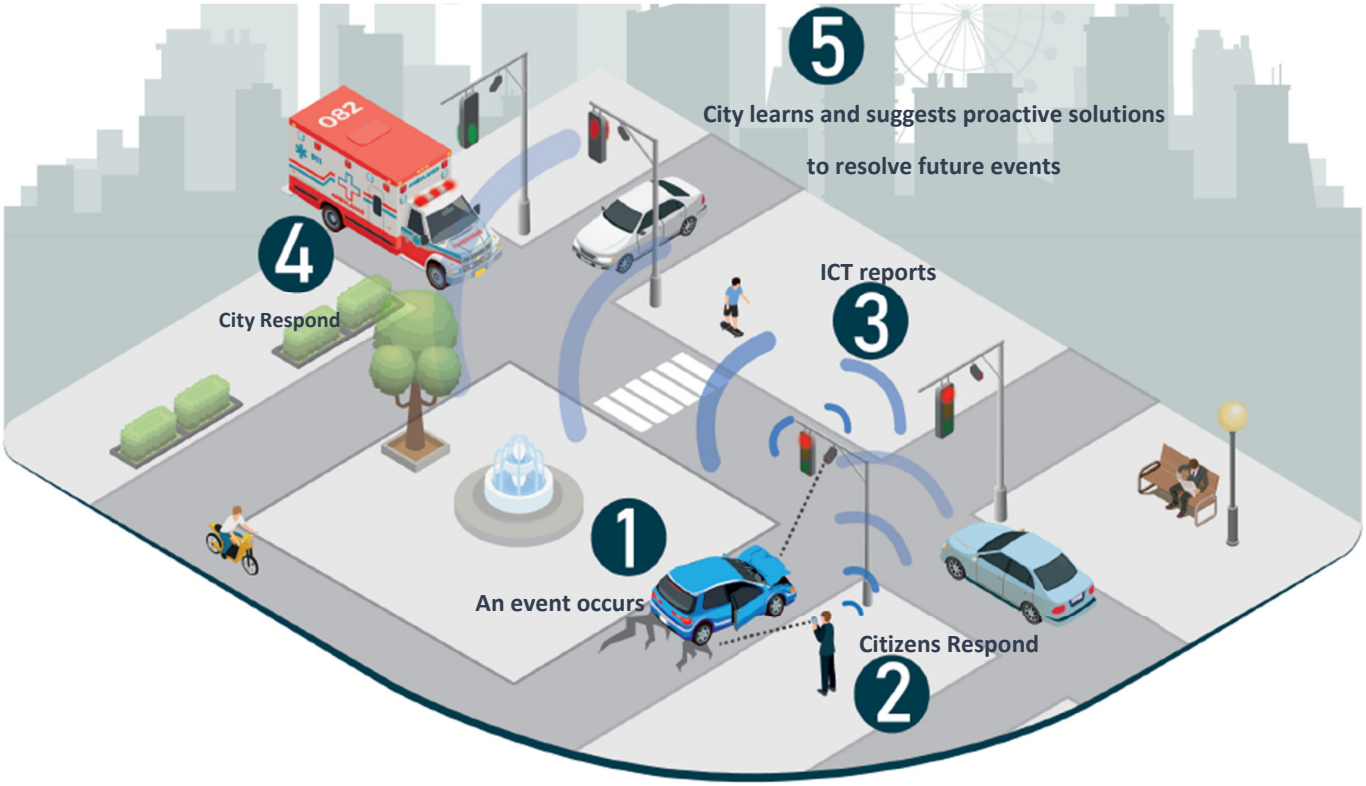

Figure 1. The concept of a cognitive city. Source: [29].

With the developing digital model, such as the cognitive city model, the future of our cities is anticipated to have a different interpretation, as well as the user experience. The concept of digitalisation has changed our perception and how we interact with the elements of the built environment, especially in the urban realm. With the advancement in technology, the future of our urban realm would articulate a novel form of living that presents new perspectives to the user experience in the urban realm of the future city.

In the last 20 years, scholars envisioned a spectrum of visions to the future of the city, the urban realm and the built environment [7,18,19,27,28]. Those visions are shaped around the ongoing transformation in the way we perceive and interact with the city and its urban realm in correspondence to the technology advancement, in particular digitalisation. This article undertakes a systematic review of literature in the last two decades to explore and investigate the themes of future city, digital twinning, the urban realm and city users.

3. Methodology

This study presents a systematic review of the literature on the future of the built environment and the role of city users in the city of the future [31–33]. The study adopts the guidelines of the Preferred Reporting Item for Systematic Reviews and Meta-Analysis (PRISMA) [34]. The PRISMA guidelines ensure that a systematic review is rigorous, transparent and reliable [34]. Figure 1 illustrates the framework of PRISMA. The systematic review traced the keywords "Future Cities", "Urban Realm", "Digital Twining" and "Users". Three major databases were utilized for the systematic review: Scopus, Science Direct and Google Scholar. Figure 2 depicts the process of the systematic review:

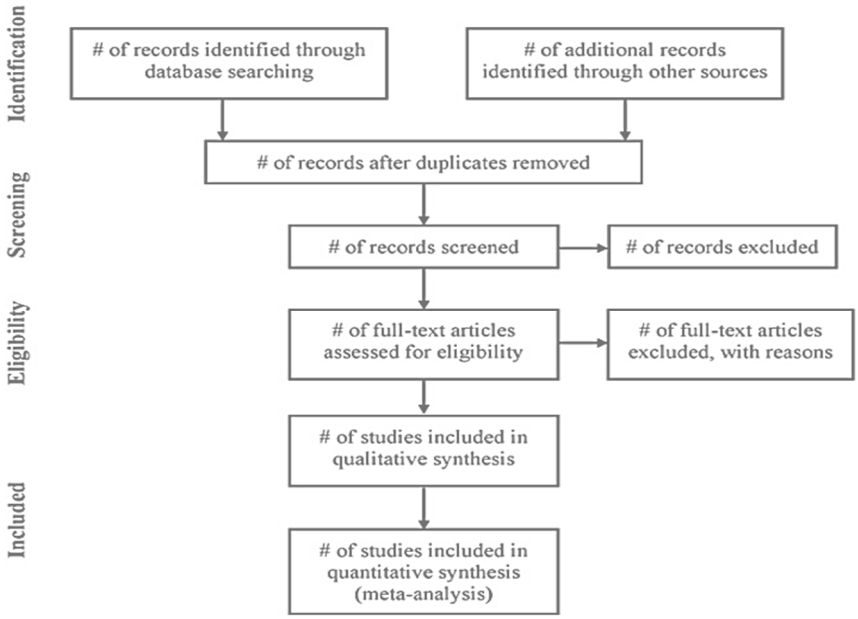

Figure 2. PRIMSA framework of literature search and review. Source: [34].

3.1. Systematic Literature Review

The systematic review process was conducted in three consecutive phases. First, relevant literature was identified and exported to a digital library. Then, the exported literature was screened and checked for duplication and relevance. Finally, the literature was assessed for eligibility and inclusion. The systematic review adopted the databases: Scopus, Science Direct and Google Scholar. Scopus was selected for its wide inclusion of peer-reviewed scientific articles, as well as its advanced searching options. Science Direct was selected for its full-text access option to peer-reviewed articles, which enhances the transparency and reliability of the systematic review. Finally, Google Scholar was selected for its largest coverage of published literature, which covers all published works, grey articles and other resources. The systematic review process was conducted with Endnote software as the digital library for data storage, screening, filtering and assessment.

3.1.1. Literature Identification

The systematic review process started with identifying literature in the last 20 years. The identification search was conducted within the three selected research databases, as demonstrated in Table 1, and with the following keywords:

("Future City" OR "Cities of the Future" OR "Future Smart City" AND "Urban Realm" OR "Future of Urban Realm" AND "Digitalization" OR "Digital Cities" OR "Intelligent Cities" AND "Digital Infrastructure" AND "Digital Twinning" OR "Digital Twin" OR "City Digital Twin" AND "Users" OR "Urban Realm Users" OR "City Users").

As demonstrated in Table 1, different search settings were adopted depending on the search system of the databases. To ensure the inclusion of maximum relevant articles, search keywords were typed as complete strings and individual strings in multiple searching possibilities. The results from Scopus and Science Direct were exported by the Export function in the two databases and with RIS format, while the results of Google Scholar were exported with Cite function and in Endnote format. Finally, the results were imported into Endnote software and then grouped around each database to prepare for literature screening.

Table 1. Literature Identification Search.

Database	Search Feature	Keywords	Results
Scopus	Advanced Search Search Category: Documents Search within: All Fields Document Type: All Timeframe: 2000–2021	All ((“Future City” OR “Cities of the Future” OR “Future Smart Cities”) AND (“Digitalization” OR “Digital Cities” OR “Intelligent Cities”) AND (“Urban Realm” OR “Future of Urban Realm”) AND (Digital Twinning OR “Digital Twin” OR “City Digital Twin” OR “Digital Infrastructure”) AND (“Users” OR “Urban Realm Users” OR “City Users”))	143
Science Direct	Advanced Search Search Category: Articles Subject Area: All Fields Article Type: All Timeframe: 2000–2021	All ((“Future City” OR “Cities of the Future” OR “Future Smart Cities”) AND (“Digitalization” OR “Digital Cities” OR “Intelligent Cities”) AND (“Urban Realm” OR “Future of Urban Realm”) AND (Digital Twinning OR “Digital Twin” OR “City Digital Twin” OR “Digital Infrastructure”) AND (“Users” OR “Urban Realm Users” OR “City Users”))	65
Google Scholar	Advanced Search Search Category: Articles Timeframe: 2000–2021	All ((“Future City” OR “Cities of the Future” OR “Future Smart Cities”) AND (“Digitalization” OR “Digital Cities” OR “Intelligent Cities”) AND (“Urban Realm” OR “Future of Urban Realm”) AND (Digital Twinning OR “Digital Twin” OR “City Digital Twin” OR “Digital Infrastructure”) AND (“Users” OR “Urban Realm Users” OR “City Users”))	86

3.1.2. Literature Screening

The acquired search results were checked for duplication and relevance in this phase. The literature identification search resulted in a total of 294 studies that were then screened considering:

- Duplications of results among the three databases: Scopus, Science Direct and Google Scholar;
- Scope and keywords of the identified studies in relation to the scope and objectives of this systematic review;
- Aim and objectives of the identified studies in relation to the research questions of this systematic review;
- Publication journal, subject area and research field of the identified studies in relation to the subject area (Built Environment, Urban Design, Urban Planning, Architecture) of this systematic review;
- Key findings and contributions of the identified studies in relation to the aim and objectives of this systematic review;

After excluding duplicated studies, the remaining studies were downloaded. The screening process involved reading the abstract and screening the content of each study, as well as checking its key findings and contributions, before downloading. At this phase, only 68 studies were selected and downloaded for further assessment. Table 2 reports the results of the literature screening phase.

Table 2. Literature screening.

Screening Criteria	Excluded Results	Remaining Results
Duplications	46	248
Study scope	39	209
Aim and objectives	51	158
Field of study and publication journal	31	127
Key findings contributions	59	68
Total results after Literature screening = 68		

3.1.3. Literature Assessment and Inclusion

After screening the literature results, the remaining 68 articles were downloaded and assessed for inclusion. These articles were reviewed against a set of inclusion and exclusion criteria developed by authors that fulfil the scope, aim and objectives of this review. The assessment involved the following inclusion criteria:

- Only peer-reviewed and full studies were selected;
- Studies discussing or investigated concepts, features, characteristics, frameworks and expected models of future cities or their urban realms and digital twinning and users;
- Studies discussing or investigating the main gears and drivers of future cities or their urban realm, and concepts of digitalization, digital twinning and users;
- Studies discussing or investigating the experience of the user, urban realm user or city user in planning, operating and enhancing the quality and performance of future urban realm.

The assessment also involved the following exclusion criteria:

- Non-peer reviewed studies;
- Studies discussing broader concepts out of the scope of this systematic review, such as smart cities, urban infrastructures and urban planning in general terms;
- Studies with redundant and repetitive scope, aim, objectives, methodology and findings.

Ultimately, the process of literature assessment resulted in the inclusion of 41 studies. Table 3 presents the scope, summary, journal name and publication year of each of the selected 41 studies.

Table 3. Nominated literature of the systematic review.

No.	Literature Title	Ref.	Document Type	Journal/Publisher	Summary
01	Future cities: Conceptualizing the future based on a critical examination of existing notions of cities	[35]	Research Article	Cities Publication Year: 2018	The study discusses the trends of the city of the future and conducts a systematic review on the conceptualization of the future of cities
02	Cities of the imagination: Science fiction, urban space, and community engagement in urban planning	[36]	Research Article	Futures Publication Year: 2011	The study discusses the relation between science fiction concepts and the urban planning of cities
03	Smart cities of the future	[37]	Research Article	The European Physical Journal Publication Year: 2012	The study presents the principles and gears of the smart city of the future focusing on the impact of technology on the transformation of cities
04	The Smart City Concept in the 21st century	[7]	Research Article	Procedia Engineering Publication Year: 2017	The study discusses the evolution of the smart city model and the drivers of the smart city notion
05	Constructing a Vision for an 'Ideal' Future City: A Conceptual Model for Transformative Urban Planning	[38]	Research Article	Transportation Research Procedia Publication Year: 2016	The study demonstrates a spectrum of views on the ideal picture of the city of the future and envisions a conceptual model on the future of urban planning
06	The future of the future city? The new urban sciences and a PEAK Urban interdisciplinary disposition	[39]	Research Article	Cities Publication Year: 2020	The study scrutinises the future city model, demonstrated by the literature, with the PEAK approach developed by authors in this study
07	Co-creating the cities of the future	[40]	Research Article	Sensors Publication Year: 2016	The study discusses the potential of technology in involving city stakeholders in creating the future of the city
08	Complexity in future cities: the rise of networked infrastructure	[41]	Research Article	International Journal of Urban Sciences Publication Year: 2017	The study demonstrates the development of ICT applications and its impact on the city's infrastructure
09	Designing Future Cities for Wellbeing	[42]	Book	Taylor & Francis Publisher Publication Year: 2020	The study presents genuine approaches in designing the future city, focused on liveability and sustainability
10	Smart sustainable cities of the future: An extensive interdisciplinary literature review	[43]	Review Article	Sustainable Cities and Society Publication Year: 2020	The study conducts a review on the trends of smart, sustainable cities of the future
11	Smart cities: A conjuncture of four forces	[44]	Research Article	Cities Publication Year: 2015	The study demonstrates the main pillars and drivers of the smart future city
12	The age of intelligent cities: Smart environments and innovation-for-all strategies	[45]	Book	Taylor & Francis Publisher Publication Year: 2014	The study illustrates the themes of intelligence and environment in cities, and discusses strategies on the potential of a better environment in the intelligent city model
13	Making the digital city: the early shaping of urban Internet space	[28]	Book	Taylor & Francis Publisher Publication Year: 2016	The study discusses the early shaping of the digital city notion and the main gears of the notion
14	Mobility, citizens, innovation and technology in digital and smart cities	[46]	Research Article	Future Internet Publication Year: 2020	The study investigates the themes of mobility, people and technology in the digital city
15	The urban digital lifestyle: An analytical framework for placing digital practices in a spatial context and for developing applicable policy	[47]	Research Article	Cities Publication Year: 2021	The study demonstrates a practical framework on implementing digital applications in urban planning and operation

Table 3. *Cont.*

No.	Literature Title	Ref.	Document Type	Journal/Publisher	Summary
16	City Information Modelling: A Conceptual Framework for Research and Practice in Digital Urban Planning	[12]	Research Article	Built Environment Publication Year: 2020	The study illustrates the concepts of CIM (city information modelling) and discusses the practical applications of the CIM model
17	Applying seven resilience principles on the Vision of the Digital City	[48]	Research Article	Cities Publication Year: 2020	The study illustrates the concepts of CIM (city information modelling) and discusses the practical applications of the CIM model
18	Digital Twins for Cities: A State of the Art Review	[49]	Review Article	Built Environment Publication Year: 2020	The study conducts a review on applications of digital twinning for cities
19	A systematic review of a digital twin city: A new pattern of urban governance toward smart cities	[18]	Review Article	Journal of Management Science and Engineering Publication Year: 2021	The study conducts a systematic review on the potential of digital twinning applications in planning and governing smart cities
20	City digital twin potentials: A review and research agenda	[50]	Review Article	Sustainability Publication Year: 2021	The study conducts a review on the theme of city digital twin, focusing on its conceptualization, applications and possible outcomes
21	Smart City and Digital Twins: Definitions, Methodologies, and Applications	[51]	Book Section	IGI Global Publisher Publication Year: 2021	The study discusses the definition of the city digital twin paradigm and focuses on its possible applications and its methodological framework
22	Urban Big Data and the Development of City Intelligence	[52]	Research Article	Engineering Publication Year: 2016	The study presents the concept of big data in urban context and highlights the potential of the big data concept in developing smart and intelligent cities
23	Urban planning and building smart cities based on the internet of things using big data analytics	[53]	Research Article	Computer Networks Publication Year: 2016	The study discusses the impact of big data analytics on the urban planning of the smart city of the future
24	The rise of big data on urban studies and planning practices in China: Review and open research issues	[54]	Review Article	Journal of Urban Management Publication Year: 2015	The study presents the rise of digitalisation in urban planning and governing via reviewing case studies from China
25	Urban Systems Design: Creating Sustainable Smart Cities in the Internet of Things Era	[55]	Book	Elsevier Publisher Publication Year: 2020	The study demonstrates the potential of IoT and technology applications in creating smart cities
26	Understanding cities with machine eyes: A review of deep computer vision in urban analytics	[56]	Review Article	Cities Publication Year: 2020	The study presents a review on the city as a machine, focusing on applications of digitalisation and its potential in urban planning and analytics
27	Digital twin for 5G and beyond	[57]	Research Article	IEEE Communications Magazine Publication Year: 2021	The study discusses the themes of digital twin, 5G and IoT and presents opportunities to integrate the themes with conceptualization of the future city
28	Differentiating digital twin from digital shadow: Elucidating a paradigm shift to expedite a smart, sustainable built environment	[58]	Review Article	Buildings Journal Publication Year: 2021	The study focuses on the definition, methodology and paradigm of digital twin in the built environment context
29	Leveraging Deep Learning and IoT big data analytics to support the smart cities development: Review and future directions	[59]	Review Article	Computer Science Review Publication Year: 2020	The study conducts a review of literature on deep learning, IoT and big data themes and their role in enabling a dynamic city model
30	Shaping smart for better cities: Rethinking and shaping relationships between urban space and digital technologies	[60]	Book	Elsevier Publisher Publication Year: 2020	The study discusses the potential of integrating technology and urban planning for developing better cities of the future
31	On the sustainability of smart and smarter cities in the era of big data: an interdisciplinary and transdisciplinary literature review	[61]	Review Article	Journal of Big Data Publication Year: 2019	The study conducts a deep review on the theme of dynamic and smart cities in integration with digitalisation and its applications

Table 3. *Cont.*

No.	Literature Title	Ref.	Document Type	Journal/Publisher	Summary
32	Exploiting IoT and big data analytics: Defining Smart Digital City using real-time urban data	[62]	Research Article	Sustainable Cities and Society Publication Year: 2018	The study focuses on the concept of real-time data in urban and city planning
33	Cities and the digital revolution: Aligning technology and humanity	[63]	Book	Springer Publisher Publication Year: 2019	The study discusses the potential of aligning digitalisation and its applications with human needs, perception and desires
34	From LiDAR point cloud towards digital twin city: Clustering city objects based on Gestalt principles	[64]	Research Article	ISPRS Journal of Photogrammetry and Remote Sensing Publication Year: 2020	The study presents a practical experiment on developing a digital twin of a particular area of a city, using LiDAR and scanning applications
35	Is there anybody out there? The place and role of citizens in tomorrow's smart cities	[65]	Research Article	Futures Publication Year: 2016	The study discusses the place and expected role of city users in the city of the future
36	Increasing citizen's liveability in the future city: Responsive city, a remarkable solution	[66]	Research Article	Theoretical and Empirical Researches in Urban Management Publication Year: 2021	The study presents approaches on increasing liveability in the city of the future with applications of digitalisation
37	A review and reframing of participatory urban dashboards	[67]	Review Article	City, Culture and Society Publication Year: 2020	The study presents a practical experiment of a participatory approach in urban planning and operation, based on digitalisation and its applications
38	Challenges for connecting citizens and smart cities: ICT, e-governance and blockchain	[68]	Research Article	Sustainability Publication Year: 2020	The study discusses challenges and barriers of connecting city users with the applications of digitalisation
39	A digital twin smart city for citizen feedback	[69]	Research Article	Cities Publication Year: 2021	The study presents a practical sample of integrating city user's experience with a city digital twin
40	Understanding the use of urban green spaces from user-generated geographic information	[70]	Research Article	Landscape and Urban Planning Publication Year: 2020	The study investigates user interaction in the urban realm, using real-time geographic data
41	Urban intelligence with deep edges	[71]	Research Article	IEEE Access Publication Year: 2020	The study presents gears and enablers of cognitive learning in the urban realm

3.2. Systematic Literature Analysis

A thematic approach was adopted to analyse the selected literature and identify research trends of future cities and city digital twins in relation to the urban realm users. The thematic analysis of textual research data was adopted to systematically identify key research directions, classify research data, extract research outputs and draw conclusions [72,73]. Braun and Clarke [74] suggested a method for a rigorous and transparent thematic analysis through sifting research data in six consecutive stages: familiarizing with data, generating initial codes, identifying research themes, reviewing themes, defining themes and producing the analysis outcome. Following this thematic analysis method [74], key research directions were identified and coded, and themes were reviewed and classified to analyse results in relation to the key research questions of this study. The thematic analysis identified the main themes of this study, as presented in Table 4. Finally, the analysis results were articulated in textual format and through analytical diagrams and qualitative tables, as demonstrated in Section 4.

Table 4. Literature analysis themes.

Themes	Scope	Articles
The City of the Future - Future City Conceptualization - Future City Motives and Drivers	City Planning Urban Planning Built Environment	[7,35–45]
Digital City and City Digital Twin - Digital Twinning in the Built Environment - Digital Urban Realm - City Digital Twin	Data Computing Data Management City Planning Urban Infrastructure Urban Informatics	[12,18,28,48–62]
The Future City and City Users - Users Experience - Users as Mobile Sensors - City Users and the Future City	Engagement Dynamic Informatics Data Management Real-time Experience Urban Quality and Performance Urban Planning	[46,47,63–71]

4. Results: Future City, Digital Twinning and City Users

4.1. The City of the Future

In reviewing literature, the future city theme is found to be bound with the concepts of the digital city, sustainable city and smart city [7,37,43]. In all scenarios, literature has demonstrated a spectrum of interpretations regarding the vision to the city of the future. In order to discover the literature's vision on future cities, this section discusses the conceptualization of the future city in the literature and investigates key motives and drivers behind those concepts, which paves the way for the discussions in the following sections.

4.1.1. Future City Conceptualization

The conceptualization of the future city in literature has been labelled in various terms varying from creative cities, global cities, compact cities, eco-friendly cities and liveable cities [35]. What all of these labels have in common is their aim to depict a vision for an "ideal city" to achieve the most desirable urban experience for their users [35,38]. The conceptualization of the future city took various forms in different research disciplines [7]. In urban-related research, the concept tended to address aspects of dynamic urban realm, inclusion and innovation. In city planning research, the concept tended to address aspects of digital infrastructure, data management and interconnected city grid, whilst research related to the built environment tended to address aspects of sustainability, liveability and resilience [37,42,43,45]. Adriana Sanchez and Nick Tyler [38] have worked on constructing a vision for an "ideal future city" through conducting consecutive research investigations

across the UK, Latin America and China. The vision depicts a holistic conceptualization to the city of the future represented in five city models and illustrated in a multi-dimensional perspective that encompasses a multi-disciplinary interpretation [38]. The vision presents the concept of the future city in five primary forms: Evolving City, Active and Inclusive City, Courteous City, Healthy City and Public Space City, as demonstrated in Figure 3. The five-model figure depicts a collective picture on the concept of the future city that is discussed and demonstrated in literature. Although literature has interpreted the conceptualization of the city of the future in various forms and terms, nevertheless, there are recurring themes across different contexts, that are: smartness, sustainability, digitalization, intelligence, liveability and resilience [7,35,37,42,43,45].

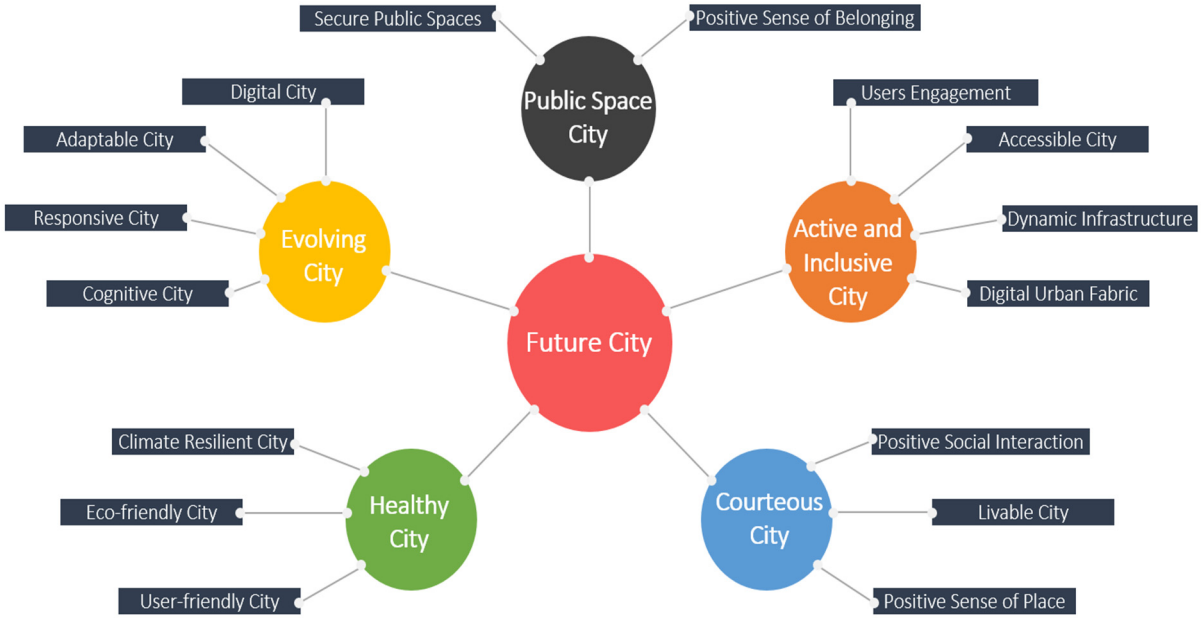

Figure 3. Future city conceptualization. Source: Authors.

4.1.2. Future City Motives and Drivers

Perhaps the trend for envisioning a paradigm to the city of the future is one of the most dominant themes in related literature. The reasons are many, and most predominantly because the city is the place we live in, interact with and navigate through. The motives behind the transformation to the "ideal city of the future" are described in various forms in literature, and among the trending motives, themes of climate change, population growth, urban expansion, technology revolution, emerging needs, evolving challenges and increasing demands are predominant [37,39,43,45]. In particular, the motives to the city of the future paradigm, as identified by the reviewed literature in this article, can be grouped around two main poles: technology push and demand pull [44]. Technology advancement and the revolution in the ICT industry enabled the investment in emerging concepts, such as smart buildings, smart transportation and smart utilities, thus creating a vast array of opportunities to redefine the features and characteristics of the built environment, especially in the urban realm [43–45]. The advancement in technology was reinforced with the increasing demand for novel solutions to react against contemporary challenges, such as urbanization, population growth and city management, which all led to the popularization of an ideal future city paradigm [37,42,44]. Beside the motives to the ideal city of the future, one of the main objectives of this systematic review was discovering the key drivers of the city of the future paradigm. To identify the key drivers of the future city paradigm, a scientometric analysis to the studied literature was conducted [75]. With VOSviewer software, the analysis sifted literature using the co-occurrence analysis method. The co-occurrence analysis method in VOSviewer identifies potential keywords and concepts that are related directly or indirectly to the enabling of a particular theme, in this case the city of

the future [75], and then produces a co-relation diagram of interrelated concepts extracted from the studied literature. Figure 4 reports the results of the scientometric analysis of the studied articles in this review analysed with VOSviewer, using the co-occurrence method.

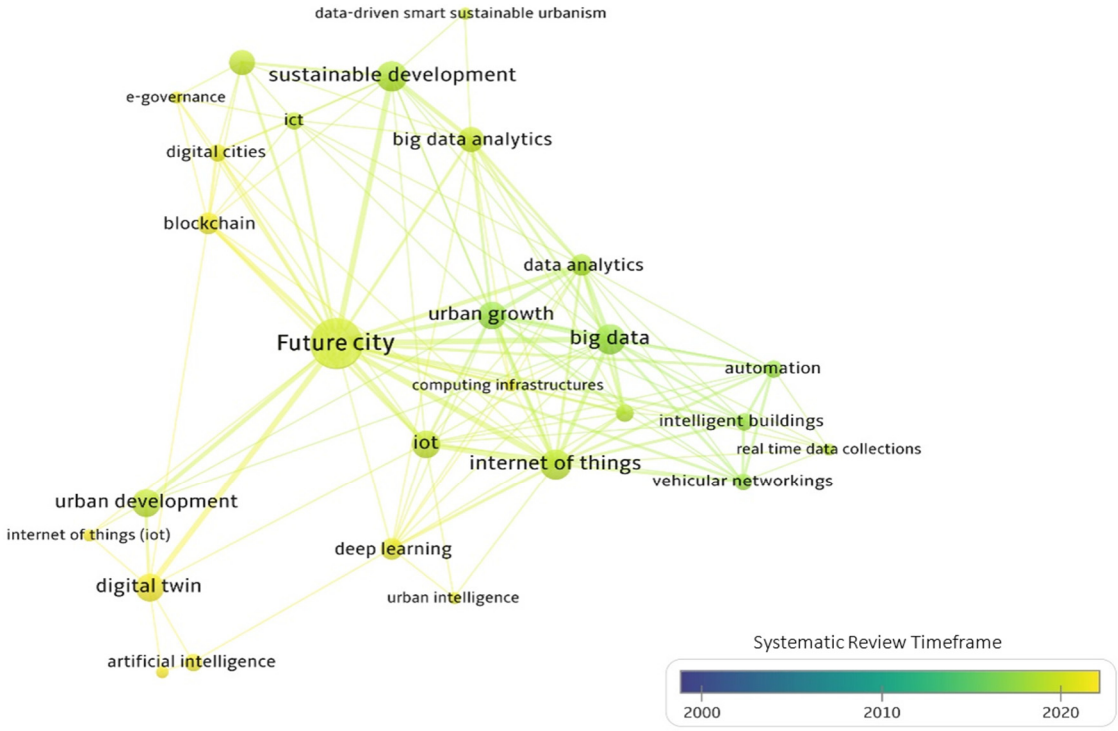

Figure 4. Scientometric analysis of literature. Source: Authors.

According to the results of the scientometric analysis, the following concepts were reported to be correlated in driving the formation of the future city paradigm: Urban Development, Automation, Urban Growth, E-governance, Big Data, Internet of Things, Deep Learning and Digital Twinning. Moreover, in review literature, those concepts were articulated to have a profound influence on the definition, structure and features of the future city paradigm. The findings in this section presented the results of reviewing the nominated literature on the conceptualization and gears of the future city paradigm, as per the literature review of this article.

4.2. Digital City and City Digital Twin

The concept of digital twinning emerged with different applications in literature in the early 2000s, most notably, in relation to engineering applications, such as manufacturing and production [49]. Definitions of the "Digital Twin" terminology were articulated differently in literature depending on the usage, applications and discipline of literature. However, the evident consensus in the literature is that a digital twin is a digital representation of a physical object [49,50,58]. In the built environment, the concept of digital twinning has been related to the conceptualization of the digital city or in other terms the city of the future, where city digital twin is seen to be an integral part of the implementation of the city of the future ambitions [12,18]. Section 4.2.1 discusses applications of digital twinning in the built environment and explores the foreseen implications of these applications on the shaping of the future city and its urban realm.

4.2.1. Digital Twinning in the Built Environment

Digital twinning is a relatively new theme in the built environment discipline. The theme emerged in parallel to the increasing call for a smarter, integrated and more sustainable built environment [49,58]. In reviewing literature, Digital Twin (DT) has been

notably related to the Digital City (DC) notion. Literature referred to the digital city as an umbrella for novel applications that could enhance the quality and performance of the built environment or the physical urban realm [28]. According to the literature, a digital city is an interconnected network of city elements that function as a system [28,48]. In order for this system to be "alive", it requires novel applications that establish a real-time connection between the physical and digital environment [28,49,58]. Digital twinning is one application that initiates a digital replica of the physical urban realm and generates a real-time flow of information between the physical and digital environments [51,57,58]. In abstraction, DC is an approach for achieving a better living experience in cities, and DT is a tool for enabling the objectives of the future digital city.

In reviewing literature on digital twinning, three main forms of digitalisation in the built environment were identified. In order to understand the potential of digital twinning in the built environment, it is crucial to distinguish between the following three digitalisation applications: building information modelling (BIM), city information modelling (CIM) [12] and digital twin (DT) [49]. Depending on scale and level of data integration, those applications have different characteristics, as illustrated in Figure 5 [12,49,50]. On the building scale, BIM applications have become a trend in recent years as a process for generating a digital copy of a physical asset, which enables an effective approach for designing, managing and maintaining a physical asset [50]. BIM includes geometrical and statistical information of a physical asset. However, it lacks real-time connection between the physical asset and its digital representation which necessitates regular "manual" updates to mirror the changes on the digital copy of a physical asset [50]. On the city scale, CIM has been introduced as a counterpart to BIM. However, CIM added one more layer of information, which is, the integration with geospatial data [12]. In CIM, city elements are incorporated in a digital model and enriched with geospatial data acquired with ICT applications. The data are linked to the digital representation of the city and utilized for city planning, urban analysis and city management applications [12,49]. Although CIM is described in literature as a more sophisticated digital replica compared to BIM [49], it remains dependent on the incoming geospatial data streamed with static sensors via different city elements, which requires regular checking and monitoring to the incoming data to mirror the physical city dynamically.

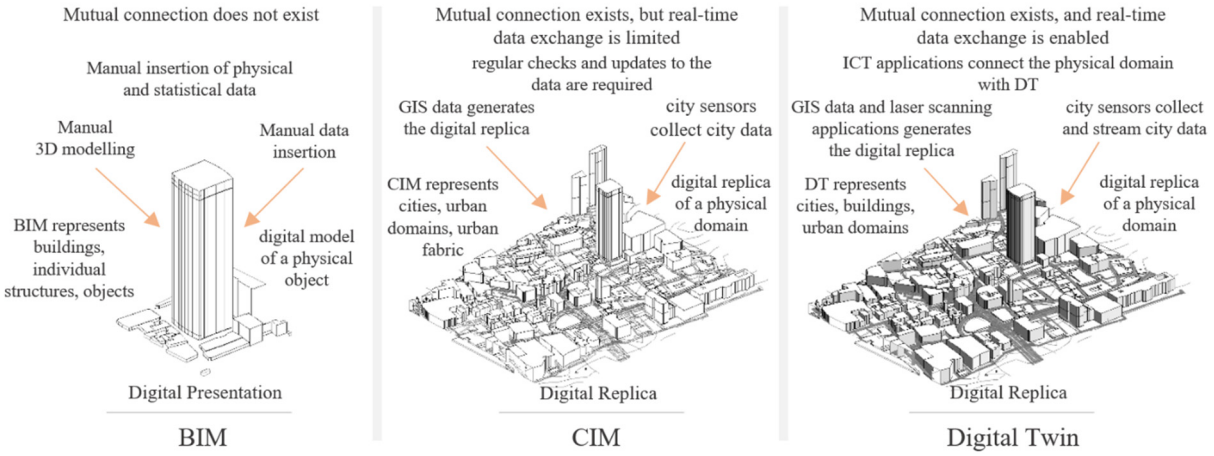

Figure 5. Applications of digitalisation in the built environment: BIM, CIM and DT. Source: Authors.

In contrast to the two previous applications, DT is described in literature to have the potential of establishing a real-time connection between the physical and digital environments [48,49,57]. Although DT is similar to CIM in methodology and applications, DT has, however, particular potential to initiate a mutual link between the physical environment and its digital replica dynamically and in real-time. In DT, the digital replica is connected to the physical urban realm in a dynamic two-way flow of data [50,57,58]. The connection is enabled via sensors by general means, whereby those sensors can sense, interact with

and measure the conditions of the physical realm, and in parallel, supply the digital twin with data, where the digital twin has the potential to learn and analyse the incoming data and supply back with possible solutions, reactions or recommendations [50,51,57]. This mutual interaction distinguishes DT from other applications of digitalisation in the built environment [50]. As per the reviewed studies [18,28,48–51], DT is a promising concept that can enable a vast array of applications to enhance the living experience, quality and performance of the physical settings in the built environment.

4.2.2. Digital Urban Realm

In order to realize the applications of digital twinning in the built environment, the physical urban realm has to be digitalized [28]. Previous research highlighted the opportunities of digitalizing the city urban realm to tackle a spectrum of contemporary city challenges [52–54,60]. A digital urban realm is an interactive digital infrastructure that links elements of the physical urban realm together, using advanced ICT applications [52–54]. In the systematic literature review, three main principles have been identified for the successful digitalization of the urban realm: interconnected urban infrastructure, urban brain and responsive applications. The physical components of the urban realm need to be linked together first to acquire real-time data regarding the ongoing interrelated activities within the physical realm. A collective data centre "data capital" is then required for sifting, filtering and analysing the incoming data in order to suggest responses accordingly. Finally, a set of applications are to respond to a particular event within the physical urban realm [18,52–55,60,62].

To construct a digital urban realm or a digital city in general terms, the three main principles have to be connected. In order to establish this connection, a shared language and a delivery method are required [52–54]. In the systematic review, literature refers to the shared language by using the term urban big data and the delivery method using the term Internet of Things [52,53,55,59,61,62]. Literature defines urban big data as massive amounts of static and dynamic data that are generated from different objects within the physical urban realm, where these data can be analysed, shared and integrated to understand the operational behaviour of the urban realm, and, therefore, make more informed decisions to enhance the quality and performance of the physical realm [52,61,62]. Urban big data is the language that describes the real-time status of urban elements, such as infrastructure, buildings, urban space, environment and other urban elements. This real-time status can be generated dynamically through physical sensors or city users. In all cases, these sensors should be connected to the urban brain (data capital) [52,61,62]. The Internet of Things (IoT) is an advanced ICT technology that establishes a real-time connection between the city elements and its users. Thus, it acts as a real-time data delivery method. With IoT, all city elements can be interconnected in a digital grid that reports real-time data to the data capital [59,60,62]. To achieve real-time connection, IoT has to be supplied with high-speed internet service, called 5G (fifth generation of the broadband cellular network). The high data-delivery speed of 5G can enable the IoT grid to stream live data acquired from all city elements in a systematic and dynamic manner [55,57,59]. To better understand the structure of the digital urban realm or the digital city in general, Figure 6 illustrates a holistic analysis of the digital city structure, as per the reviewed studies on digital cities and city digital twin in this systematic review.

Having sifted the literature on the digital city notion and digitalisation in the built environment, the next section focuses on the potential of a city digital twin in the structure of the city of the future.

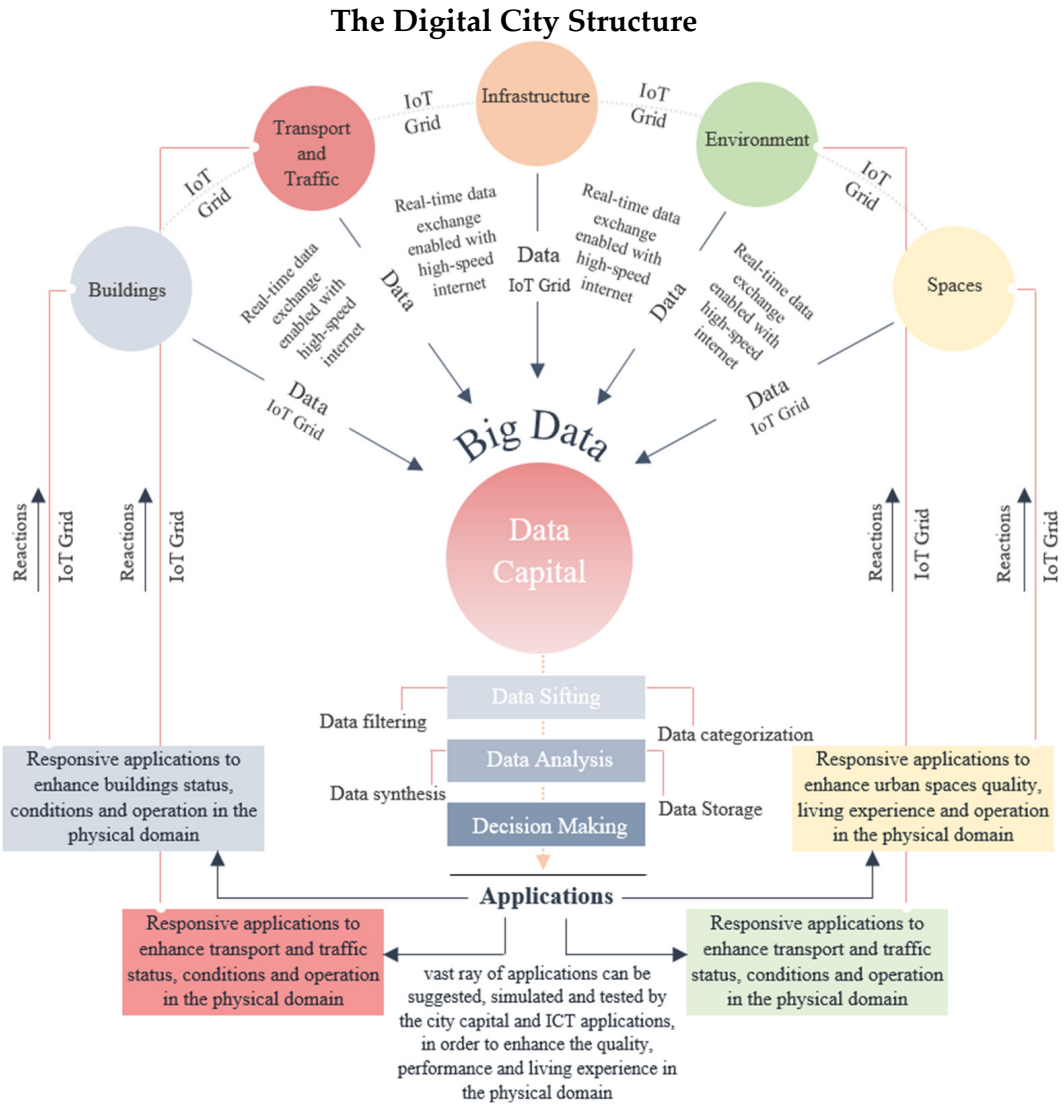

Figure 6. The conceptualization and system of digital city. Source: Authors.

4.2.3. City Digital Twin

A city digital twin mirrors the physical settings of a city [49–51]. In contrast to the other visual and graphical digital representations, a city digital twin enables a novel dimension of mirroring the physical city's assets, that is, the "mutual connection" [49–51]. The principle of digital twinning lies in forming a real-time connection between the digital representation and its physical reference [58]. On the city scale, this representation is more difficult to achieve and manage due to cities being complex living systems [64]. However, with the increasing development of ICT applications, the literature identifies the potential of the city digital twin in enhancing the management, operation and living quality of the physical city [18,50,60,64]. The literature describes city digital twins as an integral part in the development of the future city. Similar to the concept of the digital urban realm, a city would then consist of the interconnected and integrated digital and physical urban realm, all linked together in a federated digital replica of the city, that is the "city digital twin" [49–51,59,60]. The systematic review illustrated different anticipations for the potential of the city digital twin and its possible opportunities. In order to investigate the potential of city digital twin applications on the city scale, a scientometric analysis has been conducted on relevant literature on digital cities and city digital twining, using a co-occurrence method. Figure 7 demonstrates the results of the scientometric analysis.

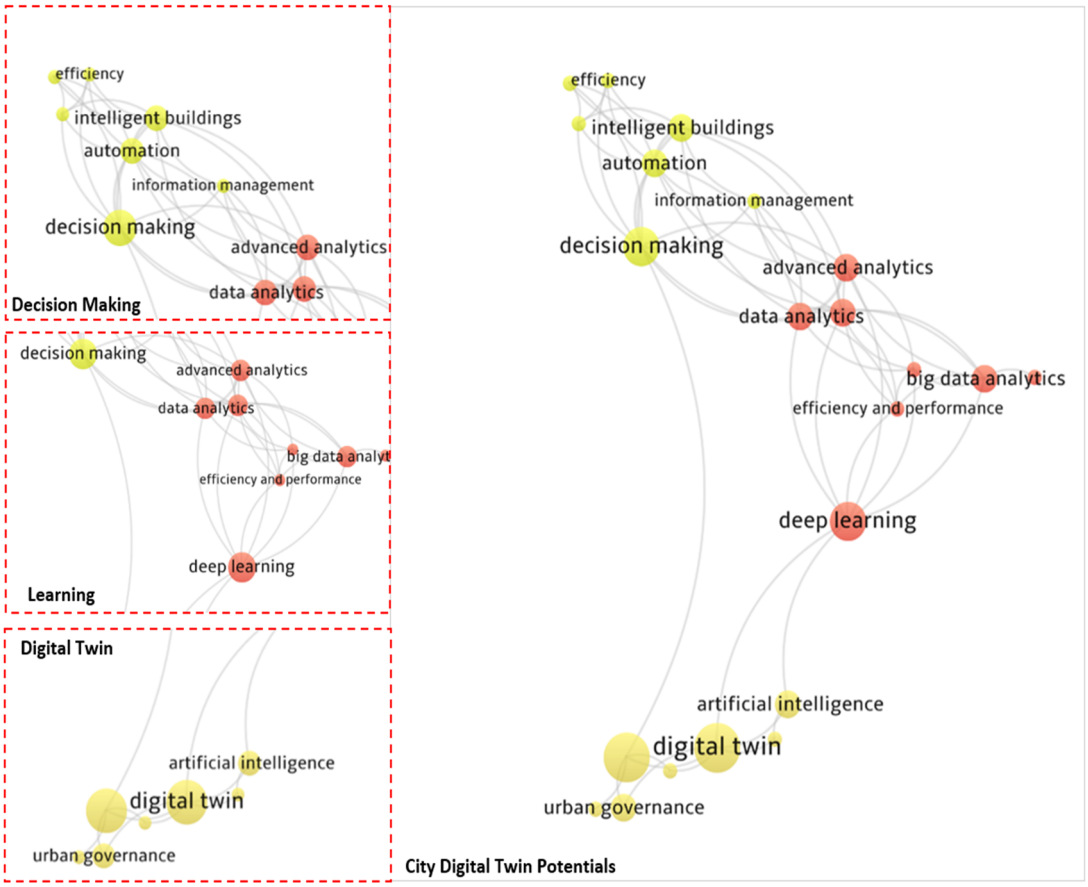

Figure 7. City digital twin potential. Source: Authors.

According to the literature, a city digital twin has two main principles in general: learning and decision making. Literature referred to the adoption of city digital twins as an opportunity to learn from the interactions between city elements, and, therefore, configure more informed decisions that would enhance the efficient management and performance of city elements. Ehab Shahat investigated the literature on city digital twin potentials to define a thematic frame for possible potentials of city digital twining [50]. He found five main outcomes for adopting a city digital twin: data management, visualization, situational awareness, planning and prediction, integration and collaboration. According to Shahat [50], the core potential of the city digital twin is managing city data in a centralized, accessible and integrated manner. The ability of the digital twin to integrate city elements in one presentation and through a mutual connection enables a new dimension in managing city data that has the potential of enhancing the efficiency and performance of the city [50]. Visualization is another potential. A city digital twin can enable real-time navigation, simulation and investigation of the city to configure more informed decisions when it comes to planning and designing city elements [50]. Situational awareness sets digital twining apart from any other city's representations. The ability of a city digital twin to establish a real-time connection with its physical city opens new dimensions for enhanced operation practices of city elements and city schemes [50]. Planning and prediction is another potential of digital city twinning. The digital twin of the city enables the testing of "what if" scenarios virtually, which assists in better understanding the behaviour of the city and predicting proactive solutions in case of different scenarios occurring [50]. Lastly, integration and collaboration; this feature allows a city digital twin to integrate various city elements, urban realms and stakeholders and open novel dimensions in better understanding the structure of the city. Such integration enables more robust decision making with the aim of enhancing the living experience, quality and performance of the city elements [50]. This systematic review highlights relations that cannot be overlooked between the conceptualization of

city digital twining [49–51,59,60] and implementation of the cognitive city [26,29,30,76], as described in Section 2 of this article. As discussed, a cognitive city can learn from past experiences and, therefore, configure more informed decision making processes that enhance the efficiency and performance of the city. Although there is no evident application in the literature regarding this assumption, the findings of this systematic review reveal the potential of the cognitive city paradigm in presenting a novel manner in perceiving our living systems, which can be an opportunity for further investigations.

At this point it is critical to recognize the positioning of the city digital twin in the digital city setting. The literature highlights the city digital twin as an integral part of the future city, enabled by big data, IoT and data computing initiatives [18,49,51]. Similar to the concept of the digital urban realm, demonstrated in Figure 6, a city digital twin integrates the relations between the city elements, events and city users [18,49,51]. The scale of the city digital twin can differ depending on the context and settings of the physical reference. Throughout the systematic review, literature has not defined a specific scale or outline to the city digital twin. It could be a portion of a city, a single urban realm or a whole city in one model. Of course, the scale and level of detail (LoD) of the twin depends on the intended purpose of the twin, for instance, whether it is data management, monitoring, planning or operation. Regardless of the scale and LoD, the city digital twin mechanism remains the same in all scenarios, which is a real-time and dynamic connection between the digital twin and its physical reference [18,49–51,58]. To elaborate the concept further, Figure 8 demonstrates the city digital twin mechanism at the city scale.

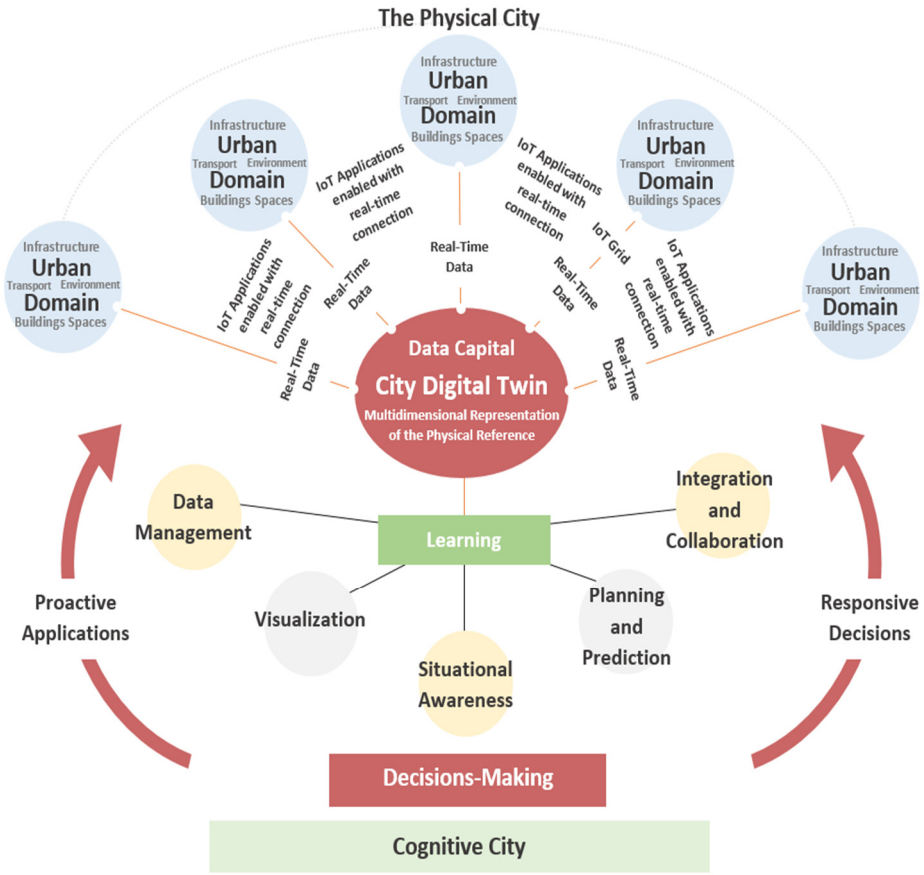

Figure 8. City digital twin mechanism. Source: Authors.

The potential of the city digital twin in enabling a new perspective for understanding, interacting with and responding to our living system opens novel dimensions in multi-disciplinary research areas that can redefine the way we perceive and interact with the city. These new manners of planning, management and operation have the potential of

enhancing the living experience, efficiency and performance of the city, its urban realm and the built environment in general. Yet, the implementation of this digital transformation on a city scale requires pre-established city settings allowing for practical ICT applications in order to acquire data in real-time, analyse the data accordingly and react to the conditions of the physical environment.

4.3. The Future City and City Users

The conceptualization of the future city reveals many scenarios in our existing cities that ought to change, be upgraded or transformed. City users are an integral part of this change and play a fundamental role in determining its implications, as any change in the settings of our living systems requires a change in the way of living of its users. This section explores literature on the theme of city user in the digital city.

4.3.1. User Experience

It is through our experience within the physical space, in which we live and navigate through, that we perceive and recognize the conditions of the physical space. With the gradual transformation of our living manner in the physical realm, our experience in the physical space is changing accordingly. The expected digital transformation in our cities, as envisioned by literature, directly impacts the experience of the city users in the physical environment [46,47,63]. The experience of city users goes beyond what they see, touch or smell and extends more to a notion of place, its configuration, quality and performance [47,63,69]. With this in mind, the way technology is redefining the experience of city users necessitates the need to discover the possible definitions of the city user in the city of the future. For instance, does technology shape the experience of city users in the city of the future? Or would the city of the future be planned upon the requirements of its users? To investigate the definition of city user in the city of the future, a word-cloud analysis was conducted on the experience of city users in the future city. The word-cloud analysis was conducted through reviewing related literature and identifying repetitive concepts associated with the definition, role or experience of city users in the city of the future model. Figure 9 illustrates the word-cloud analysis results.

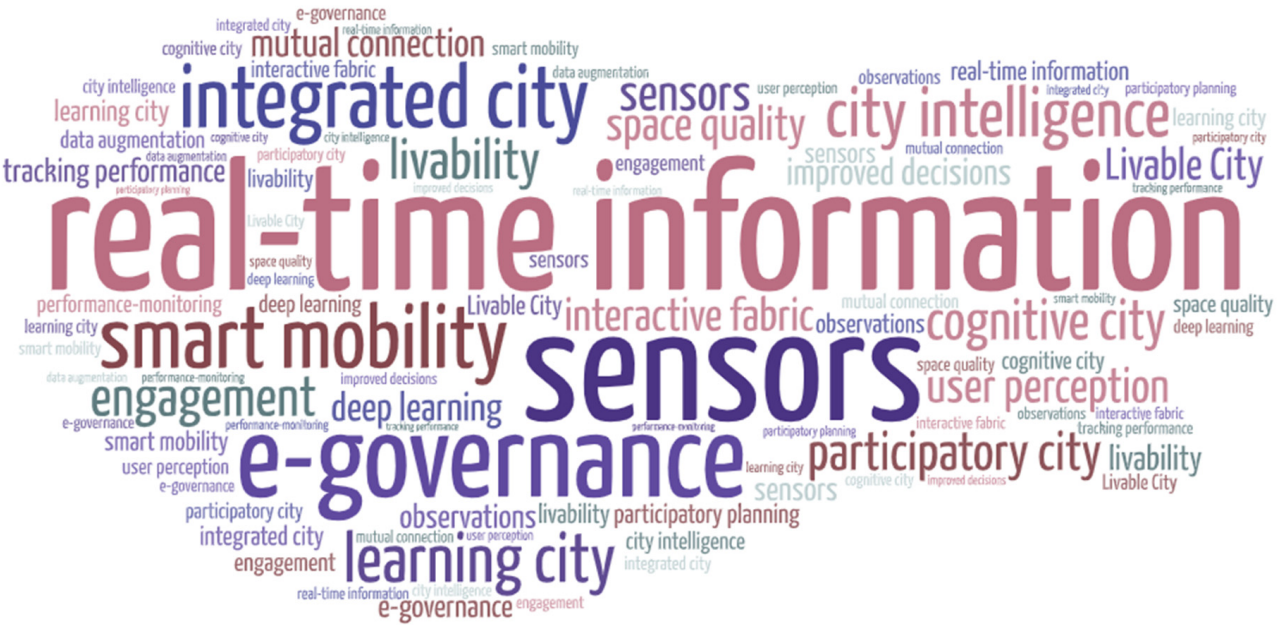

Figure 9. Word-cloud analysis of literature on the experience of the user in the city of the future. Source: Authors.

As illustrated in the analysis, real-time information and users-as-sensors concepts were evolving in literature. As described by Allam and Heikinheimo [63,70], city users

can function as mobile sensors within the fabric of the city, acting as a dynamic source of real-time information and collecting a vast range of data on different events within the city fabric [63]. Within this model, the user experience in the city is reported in different data sets such as observations, interactions or perceptions and streamed to the city data capital. The data capital analyses the conditions and events within the physical realm and responds back with solutions, suggestions or reactions [66,68,70]. Not only data streaming, the literature discusses new perspectives to the role of city users in the future city, such as the concept of e-governance. E-governance is expected to enhance the engagement level of city users leading to the formulation of a participatory city, where user's experiences are heard, shared and considered [67,68,71]. Furthermore, the experience of city users can be explored and analysed to understand the perception of city users to city elements, and, therefore, learn about the conditions of the physical realm and plan for more informed decisions with the potential to enhance quality and performance of the physical realm, based on user perception [66,67,70].

4.3.2. Users as Mobile Sensors

Remote sensing in the built environment has always been linked to a form of physical devices programmed to sense a spectrum of measures or a particular measure for a specific purpose. With the revolution of the ICT industry, the conceptualization of remote sensing has developed to present new forms of remote sensing, that is, dynamic remote sensing [63,68,70]. Dynamic remote sensing articulates a novel perspective for measuring the physical environment, enabled with IoT features and real-time data exchange. In contrast to the common static sensing devices, a dynamic sensing method enables a vast vision to the conditions of the physical realm [65,67,69,70]. In recent literature, city users were proposed as a potential source of dynamic sensing [70]. The interactions of city users within the settings of the physical city presents a valid source of qualitative and quantitative data articulating a novel recognition to the spatial configuration, condition and character of the physical realm [65,67]. The study by Heikinheimo et al. [70] investigated the interactions of city users within the urban realm in the city of Helsinki, Finland. The study defined city users as a dynamic source of geolocation data and then investigated the user-generated data in spatial analysis, depending on the experience of city users in the city of Helsinki. As demonstrated in Figure 10, the study [70] considered city users as dynamic sensors to the physical realm. The study classified data sources into four main classifications: social media data, mobile phone data, sport tracking data and GIS data. All the data sets were streamed by city users, using geolocation referencing, and were presented in different forms of diagrams depending on the source of data and the activity performed by the city users.

In reviewing related literature, different studies have discussed the definition of city users and user experience in the city of the future. The model of user-generated data and user-as-mobile sensor has been investigated in different applications and through different practices, all of which aimed to align technology with humanity for the benefit of city users [63,66,67,70,71]. For instance, the studies conducted by White et al., (2021) and Heikinheimo (2020) [69,70] investigated the potential of integrating user-generated data with the planning and operation of the future city. Those studies have considered city users as dynamic sensing objects within the settings of the physical realm, where real-time information on a vast range of city events and interactions can be obtained dynamically through the city users. In recent literature, city users are being discussed as an integral part of the data-driven city, so-called "digital city". The model of users-as-mobile sensors has been highlighted in different scenarios and various applications that are seen to improve our understanding of the settings and conditions of the physical built environment.

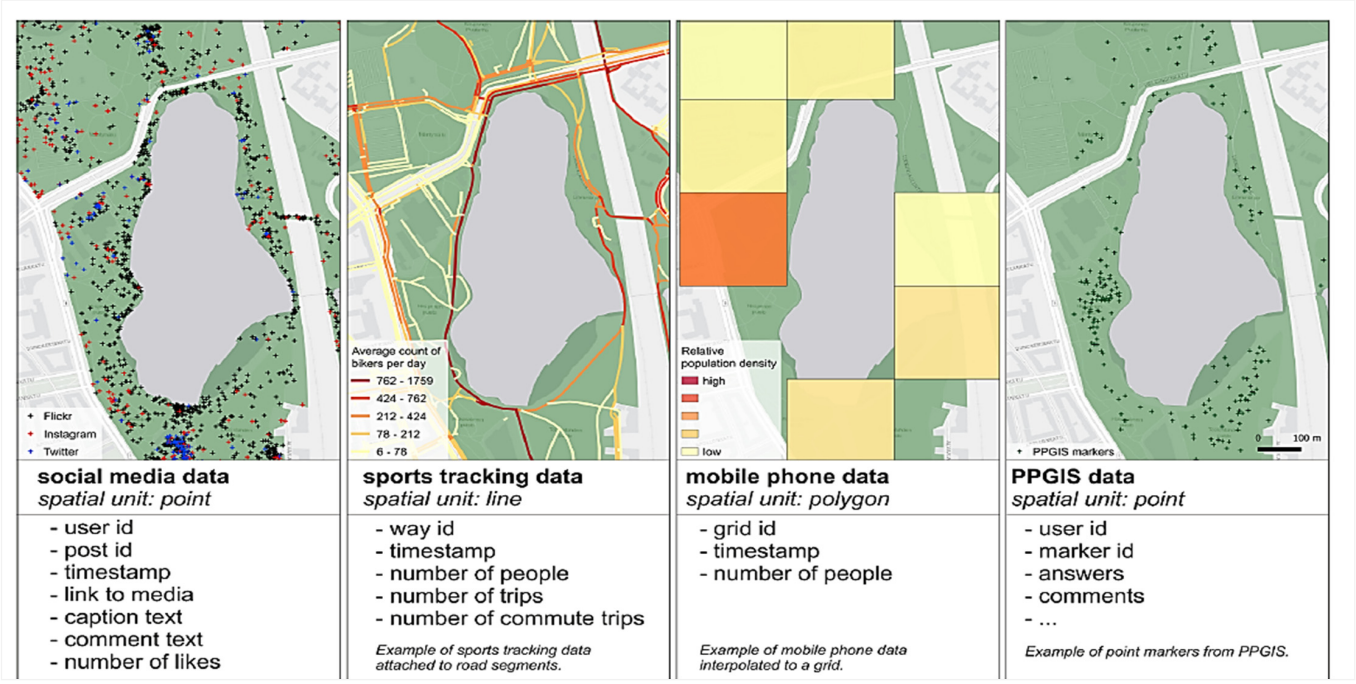

Figure 10. User-generated data for urban spatial analysis. Source: [70].

4.3.3. The Future: City Users and the Future City

The definition of city users in the future city remains a point of discussion in related literature. Ranging from realistic scenarios to science-fiction, literature has been contemplating different definitions of city users in the future city [63,65,66]. Most of these perspectives are aimed to actively engaging city users in planning, governing and shaping the settings of their existing cities [67–69]. For instance, a study [65] by Alberto Vanolo discussed different scenarios on the role of city users in the city of tomorrow, and those scenarios were dependent on the conceptualization of digital citizenship. Literature refers to the opportunity of integrating the experience of city users within the settings of the future city to facilitate different events and interactions that could enable new dimensions for understanding, interacting with and improving the liveability in our cities [67–69].

Literature also highlights the potential of integrating applications of digital twin technology with the city users through pointing out to the opportunity of establishing a form of mutual connection between the city digital twin and city users [69]. This sort of connection would enable the city user to be an integral part of planning, monitoring and managing their city. The potential of linking user experience with the city digital twin many extend beyond the participatory perspective [67–69]. However, it is worth noting that the future of city users is still limited to theoretical assumptions and yet to be discovered in realistic and tangible applications [63,65,68], which necessitate practical research and applications on the future of city users with consideration to the evolving technologies such as digital twinning. Across different studies that were reviewed in this article, the model of the cognitive city was articulated in different themes as the vision to the ideal future city. The city that can learn, interact and respond to different events and conditions to improve liveability and quality to its citizens. In order for the cognitive city model to function, technologies such as IoT, big data and digital twinning were described as key pillars in paving the way for configuration and implementation of the cognitive city model.

5. Conclusions

This article conducted a systematic review of literature on the themes of future city, its urban realm, digital twinning and the city users. Following the rigorous PRISMA methodology for reviewing literature systematically, this article reviewed the conceptualization and

configuration of the ideal future city model in association with the themes of the cognitive city model, digital twin technology and city users. The article highlighted the vision, trends and drivers of the future city through a systematic literature analysis to the gears, features and characteristics of the future city model. Most importantly, the systematic review in this article drew attention to the digital city model and its applications, in particular digital twinning in the urban realm, and its expected implications on reshaping the future of our cities. Moreover, the systematic review inquired literature on the expected definition of the city user and user experience in the city of the future. The following is a summary of the main outcomes:

- The conceptualization of the future city has been articulated in the literature in different forms and themes. However, the literature shared a common vision on the ideal future city paradigm that is: digital, interconnected and cognitive city model.
- The main motives towards the future city model, as commonly discussed in the literature, are the result of: demand pull and technology push. Through which new perspectives, trends and applications are emerging.
- In contrast to other digital representations, digital twin technology introduces a novel form of interaction between a physical realm and its digital replica. This mutual connection is opening a spectrum of promising applications with the potential to better plan, manage and operate the settings and conditions of the physical realm.
- City digital twin could be an integral part of the cognitive city model. The cognitive city that can learn, interact and respond to the conditions and events within its settings with particular potential of enhancing the living quality, performance and operation of the city.
- The definition of the city user in the city of the future remains a point of discussion in related literature. With the emerging ICT applications, literature envisions user experience to reflect new forms of interactions represented by concepts of users-as-sensors and articulated through evolving applications such as digital twinning.

The systematic review in this article presented a thorough analysis of literature focusing on the future city model, the urban realm, digital twinning and city users. The outcomes of this review suggest further research on integrating practical applications of digital twinning with the configuration of the future city model and in relation to the city users in the urban realm.

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