Review

City Digital Twin Potentials: A Review and Research Agenda

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Abstract: The city digital twin is anticipated to accurately reflect and affect the city's functions and processes to enhance its realization, operability, and management. Although research on the city digital twin is still in its infancy, the advancement of the digital twin technology is growing fast and providing viable contributions to augmenting smart city developments. This study reviews the literature to identify the current and prospective potentials and challenges of digital twin cities. A research agenda is also proposed to guide future research on the city digital twincity digital twin to reach the utmost level of a comprehensive and complete city digital twin. Enhancing the efficiency of data processing, promoting the inclusion of socio-economic components of the city, and developing mutual integration between the two counterparts of the digital twin are proposed to be the future research directions to achieve and utilize a completely mirrored city digital twin.

Keywords: city digital twin; 3D modeling; smart city; thematic analysis

1. Introduction

Smarting the city is a complicated process due to the complexity of a city. The city is not an automated system that can be easily understood and predicted, but rather a living system that evolves every day through variations and developments of its physical constructs, economic and political activities, social and cultural settings, and ecological systems [1]. The smart city concept has developed from controlling the city's physical growth to a broad concept comprised of physical, social, and knowledge infrastructures [2,3]. Although some have seen it as an ambiguous concept that entails unclear implications, or as a driver rather than a solution for urban and social problems such as inequality, social polarization, and gentrification [4,5], there is still a large amount of research that suggests the prospective benefits of smart cities in terms of sustainability, efficiency, optimization, collaboration, and innovation in the city [6,7]. Especially now, under the massive attack of the COVID-19 pandemic, where several domains such as education, transportation, and entertainment have been strongly affected, the call for smarting the city and digitizing its services is becoming more relevant and critical [8].

However, while the physical form of the city has been represented in 3D models, providing a graphic visualization of the city's physical elements, other employments of 3D models of cities have been developed for further uses such as infrastructure planning, disaster management, and energy demand estimations [9]. Recently, the evolution of 3D models has been gaining high research attention in several fields, such as aerospace and manufacturing, and architecture, engineering, and construction (AEC), which has led to the digital twin. The digital twin concept refers to developing a mirrored digital counterpart to a physical system and linking their information throughout the physical counterpart's life cycle [10]. This revolutionary technology has demonstrated successful applications in production science, such as production planning and control, maintenance, and product life cycle [11]. The digital twin is expected to enhance architectural modeling as a progressive step that develops from building information modeling (BIM) in the AEC field [12]. It

is also suggested that utilizing digital twins would contribute to smarting the city and enhancing its sustainability [13]. However, distinguishing digital twins from other types of models is crucial to realize the applicability of utilizing the completely mirrored digital twin for city-scale modeling; that is, the level of data integration, which varies according to the type of model, between the two counterparts (digital and physical) of the digital twin is decisive in stating whether the developed model is a digital twin or not [11]. Due to the complexity of the city system, for instance, integrating social and economic functions, following the proven benefits of a completely mirrored digital twin in other fields such as manufacturing and aerospace, is expected to be challenging, and may be unlikely to ever be realized [14]. Therefore, an explicit identification of the prospective benefits, as well as the challenges and requirements, of developing digital twin cities is essential to expedite the efforts towards smarting cities.

This paper aims to clarify the potentials of the city digital twin and highlight the challenges that may hinder the full utilization of this technology. For that purpose, firstly, we review the state of the art of the city digital twin and the level of development that has been reached so far by identifying the current and prospective benefits and challenges. Secondly, we develop a research agenda to demonstrate the requirements of creating a wholly mirrored city digital twin. This may contribute to advancing digital twin technology and thus enhancing the management, operations, and sustainability of the city. Developing a research agenda for digital twin cities would expedite the research and development efforts toward maximizing the utilization of digital twin technology in raising awareness about the city's activities, processes, and future trends. Moreover, politicians and city managers would gain valuable benefits of the advanced city digital twin technology by having access to more insightful information and a better understanding of their cities.

The structure of the paper is as follows: An overview of digital twin cities' potentials for smart cities, the shift from utilizing 3D models to digital twins, and an example of digital twin cities' development are presented in the next section. The methods and materials used for the review are then described in Section 3. In Sections 4 and 5, thematic classification of the city digital twin potentials, in addition to the challenges toward the full utilization of the city digital twin, will be presented. Section 6 will provide a discussion and the research agenda proposal, and finally, the paper will be concluded with research implications in Section 7.

2. Background

2.1. City Digital Twin for a Smart City

The smart city is gaining significant attention worldwide to sustain the city and improve its citizens' quality of life. When seeking to explore digital twin cities' potentials for smarting the cities, one needs to shed light on what benefits smart cities may bring about to the city. For instance, a smart city can be seen through three components, technological, human, and institutional, where the main domains can be seen as transportation, environment, energy, healthcare, safety, and education [15]. Kumar et al. designated four key areas as essential for developing smart cities: planning, physical infrastructure, information and communications technology (ICT) infrastructure, and smart solutions; more domains were added for applying smart solutions such as disaster management, tourism services, and economic processes [16]. A smart city approach was recognized as contributing to boosting the sustainability of cities environmentally and economically, and improving the delivery of services to their inhabitants [17]. In addition, smart city development is perceived as a process of building the capacity of the city's economic, social, and institutional infrastructures to enhance and conserve quality of life, socio-economic development, and natural resources [18]. The benefits of developing smart cities are anticipated to cover almost all city functions and domains, whether social, economic, and environmental aspects, or physical, institutional, and citizen-oriented developments.

The smart city is depicted as utilizing cyber-physical intelligence to improve city functions, job creation, and public satisfaction [19]. Thus, utilizing technological advancement

is at the core of smart cities, and consequently, investigating the advancements of the city digital twin is likely to be a valuable contribution. The city-scale digital twin is anticipated to reflect all city domains and systems on a digital platform, which would improve the city's visibility, realization, and operability, and thus guide smart city development. The city digital twin is expected to enhance city management and operations to achieve a smarter and sustainable city and a higher quality of life for its citizens.

2.2. From 3D Model to Digital Twin

A clear distinction between digital twins and orthodox 3D models in the AEC and urban planning fields is necessary to recognize the possible potentials of a smart city digital twin. Notwithstanding the research on the digital twin in the industrial and manufacturing field being more pervasive, there have been ambiguities in differentiating the completely mirrored digital twin from digital models and shadows. However, Kritzinger et al. have set the digital twin apart based on the level of data integration between the virtual and physical counterparts being full and mutual integration [11]. A clear boundary ought to be drawn between 3D models and BIM on one side and the digital twin on the other. In general, a 3D model is a sort of digital visualization of a physical project, whether the project is a building, infrastructure facility, or city. Generally, it enhances the efficiency and efficacy of AEC professionals, and urban planners work through the life cycle of the project: design, construction, maintenance, and even marketing [20]. As one of the key technologies in AEC, the BIM paradigm has emerged as a more intelligent process of 3D modeling that integrates and manages all the information of the physical entity, providing remarkable cost and time savings [21]. Among the many benefits of BIM, reducing errors, improving collaboration, and enhancing an organization's image are the most recognized by construction contractors [22]. Recently, BIM benefits have been suggested to be amplified when employing virtual reality (VR) tools and neural network learning models to enhance collaborative workflow and support decision management during the life cycle of construction projects [23,24]. Moreover, the integration of BIM and geographic information system (GIS) is anticipated to merge the benefits of modeling buildings and their surrounding environment, but applications on the urban environment scale are, as yet, widely unutilized, in addition to having other challenges such as data interoperability, open standards, and visualization integration [25,26].

On the other hand, a digital twin can be perceived as an opportunity to enhance city planning and operability [12]. This perception is based in the concept of developing a virtual mirror of the city, in which all the elements that constitute the city are represented on that virtual model. The main advantage of a digital twin over BIM is the interaction between physical reality and the virtual model. In BIM, the model encompasses the physical entity's geometrical and temporal information, yet it requires manual data insertion for updates due to the lack of linkage between the model and the physical entity, whereas utilizing a digital twin can provide mutual interaction between the two counterparts in real-time. For instance, using sensors and Internet of things (IoT) technologies can provide the transfer of information, which updates the virtual model according to the physical counterpart's live updates. Furthermore, due to the potential of performing simulations on the virtual model, future forecasting and optimization of the physical entity's performance are realizable, and thus the optimization of the physical counterpart's performance can be achieved [13].

However, due to the city's complexity, several challenges are yet to be explored in the city digital twin. For example, a large-sized model of a city would impose challenges regarding data handling and processing. In addition,, the divergent activities and relationships in the city, unlike manufactured products, would impose other kinds of challenges regarding data acquisition and interpretation. Identifying such challenges is necessary for designing a roadmap for research about developing a completely mirrored city digital twin.

2.3. The Digital Twin of the City of Zurich

One of the advanced digital twin cities is the Zurich city digital twin. As an important part of the smart city strategy of the city, the digital twin of the city of Zurich was developed for supporting decision-making in the city via a digital spatial image [27]. Schrotter and Hurzeler presented in their work how the city digital twin may enhance city administration and support urban planning decision-making [27]. They described the process starting from data acquisition, which is based on the spatial data of the existing 3D city model. The 3D model consists of three main models: terrain model, block model, and roof model. The data of these models are obtained from LiDAR images for the terrain model, floor plans from the city cadastral survey for the block model, and semiautomatic photogrammetry for the roof model, with three levels of detail (0, 1, and 2). The Zurich digital twin enables the visualization of street spaces, underground utilities, and chosen public buildings with higher levels of detail. For improving interoperability and data retrieval, spatial data and metadata were defined and described in detail in a federal act that was the base for developing the digital twin governance framework [27].

To enable the use of the digital twin, open governmental data is being utilized in order to facilitate contributions from the different stakeholders and their accessibility to the city data. Furthermore, a geoportal was developed that facilitates the collection of the automatically updated geodata, in addition to developing a viewer on the digital twin that enables visualizing the 3D components of the city and ongoing construction projects. Furthermore, several benefits and various applications were exercised and found useful in the context of urban planning decision-making, such as comparing and evaluating different urban development scenarios, integrating urban climate issues in development plans, and facilitating public participation in planning. The digital twin of the city of Zurich shows high potential for improving the visualization and planning of the city and the inclusion of stakeholders. However, the model requires further development. For instance, there is a need to increase the level of detail of the buildings and other city elements, integrate BIM and GIS applications to maximize the use of their potentials, and reduce the time between data updates and the 3D model processing time [27].

3. Methods and Materials

Research about the city digital twin is still in its infancy, yet some research has been conducted on employing a digital twin in smart cities. However, to develop a clear research agenda in that emerging topic, a more holistic approach is required. This paper aims to develop a research agenda by identifying potentials, challenges, and requirements for future research utilizing digital twin technology to smarten the city and enhance the operability, sustainability, and quality of life. For that purpose, literature reviews can help develop research agendas and evaluate the state of the art of any given topic [28]. Following the PRISMA guidelines [29], the process of identifying, screening, checking eligibility, and including the final articles of the data set for review was set (Figure 1).

3.1. Data Collection

This review's focus is on the city digital twin scale and its applicability, and on identifying how far the current research has achieved its goal, to draw a research agenda that can lead future research on the city digital twin. Thus, the search was performed on papers that addressed the digital twin on a city scale in three major search engines, which are among the largest databases for multidisciplinary research: Scopus, Web of Science, and Google Scholar. To expand the pool of studies that may contribute to enhancing knowledge about the digital twin on a city scale, digital twin research on scales that were larger than the building was also considered, as it would be analogous to the city digital twin. Thus, the search strings were widened to include built environment, urban environment, and district. Using the topic filter in Web of Science, which leads to finding data out of Title, Abstract, and Keywords, the search strings for both Scopus and Web of Science were identical; however, for Google Scholar, it was necessary to change the search string due

to the absence of such a filter and the enormous number of unrelated outputs that was brought about when using the same search string. Therefore, we utilized a different string that could generate as many outputs as possible that were related to our main topic. As a result, 171 published article outputs were generated up to the date of performing the search on 2 October 2020 (Table 1).
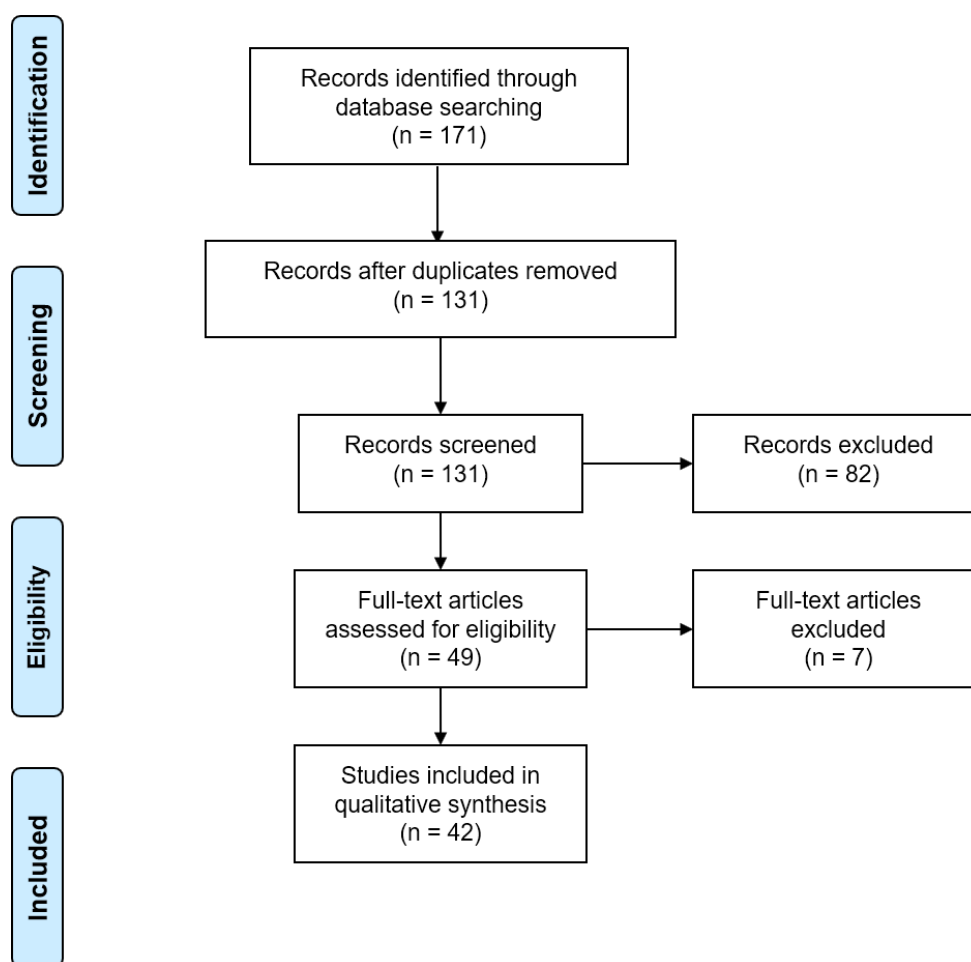

Figure 1. PRISMA flow diagram.

Table 1. Data collection and search strings.

Search Engine	Search Strings	Outputs
Scopus	TITLE-ABS-KEY ("digital twin" AND city OR "built environment" OR "urban environment" OR district)	77
Web of Science	TOPIC:("digital twin" AND (city OR "built environment" OR "urban environment" OR district))	26
Google Scholar	"city digital twin" OR "urban environment digital twin" OR "built environment digital twin" OR "district digital twin."	68
Total		171
Total articles for review	after removing duplications and irrelevant articles	42

3.2. Inclusion and Exclusion Criteria

The data collection's main inclusion criteria included the papers that addressed developing digital twins for a city or a neighborhood scale, to ensure more rigorous research findings, articles, reviews, and conference proceedings articles were considered. In addition, since city digital twin research is still in its infancy, both theoretical and empirical research were considered to explore it fully. However, non-peer-reviewed articles and those published in languages other than English were excluded, in addition to research that focused on one building or a small infrastructure project, to address the challenges of developing a city-scale digital twin solely. As a result, out of the 171 articles that resulted from the search hits, 40 articles were excluded due to duplication among the three search engines. After screening the remaining 131 articles' abstracts, 82 articles were found irrelevant, or they investigated the development of a digital twin on a smaller scale, such as a building or an infrastructure project. However, some articles were considered for the review despite their focus being on infrastructure projects. The authors perceived potential benefits in these papers for the city-scale digital twin, whether due to the large scale of the project being researched or the relevancy of the attributes of the developed digital twin in the article to the prospective complexity of the city-scale digital twin. Thus, 49 articles were considered for the review process, and while scanning these articles, seven articles were further excluded for not focusing on the city digital twin, so the full data set became 42 articles.

3.3. Analysis

In Table 2, the main characteristics of the 42 articles are presented. A descriptive analysis of the dataset shows that the attention to the city digital twin started very recently in 2017. Then interest grew very fast, from one conference paper published in 2017 to more than 20 conference and journal papers published in the first nine months of 2020. Out of the 42 articles, 20 articles were published in journals while the others were conference papers, and this was expected due to the recency of the topic. As for the countries of origin of the studies, the most notable contributor to city digital twin research was the USA with 12 articles, followed by the UK and Germany with 6 and 4 articles, respectively.

Table 2. Main characteristics of the final dataset.

Title	Year	Country	Type of Publication
Using big data analytics and IoT principles to keep an eye on underground infrastructure	2017	USA/UK	Conference Proceedings
Modeling trees for virtual Singapore: From data acquisition to CityGML models	2018	Singapore	Conference Proceedings
Smart city platform enabling digital twin	2018	Finland	Conference Proceedings
Smart city digital twins	2018	USA	Conference Proceedings
Simulation as an effective instrument for strategic planning and transformation of smart cities	2018	Russia	Conference Proceedings
Engaging citizens with urban planning using city blocks, a mixed reality design and visualisation platform	2019	UK	Conference Proceedings
Urban intelligence: a modular, fully integrated, and evolving model for cities digital twinning	2019	Italy	Conference Proceedings
From urban modelling to city digital twins: What role for the stakeholders?	2019	UK	Conference Proceedings
Mapping local vulnerabilities into a 3D city model through social sensing and the cave system toward digital twin city	2019	USA	Conference Proceedings

Table 2. *Cont.*

Title	Year	Country	Type of Publication
Digital twin, virtual reality and space syntax: Civic engagement and decision support for smart, sustainable cities	2019	Germany/ Netherlands	Conference Proceedings
Methodological framework for digital transition and performance assessment of smart cities	2019	Bulgaria	Conference Proceedings
AI-based physical and virtual platform with 5-layered architecture for sustainable smart energy city development	2019	Republic of Korea	Journal Article
Disaster City Digital Twin: A vision for integrating artificial and human intelligence for disaster management	2019	USA	Journal Article
Devising a game theoretic approach to enable smart city digital twin analytics	2019	USA	Journal Article
City services management methodology based on socio-cyber-physical approach	2019	Russia	Conference Proceedings
Developing a city-level digital twin—propositions and a case study	2019	UK	Conference Proceedings
Marking the city: Interactions in multiple space scales in virtual reality	2019	Germany	Conference Proceedings
Hybrid automaton implementation for intelligent agents' behavior modelling	2019	Russia	Conference Proceedings
Integration of 3D objects and terrain for 3D modelling supporting the digital twin	2019	Australia	Conference Proceedings
The potential of digital twin model integrated with artificial intelligence systems	2020	Italy	Conference Proceedings
A socio-technical perspective on urban analytics: The case of city-scale digital twins	2020	UK	Journal Article
Developing a digital twin at building and city levels: Case study of West Cambridge campus	2020	UK	Journal Article
Smart city digital twin-enabled energy management: Toward real-time urban building energy benchmarking	2020	USA	Journal Article
Geospatial artificial intelligence: Potentials of machine learning for 3d point clouds and geospatial digital twins	2020	Germany	Journal Article
Wearable biosensor and hotspot analysis-based framework to detect stress hotspots for advancing elderly's mobility	2020	USA/Republic of Korea	Journal Article
Participatory sensing and digital twin city: Updating virtual city models for enhanced risk-informed decision-making	2020	USA	Journal Article
Research on construction of spatio-temporal data visualization platform for GIS and BIM fusion	2020	China	Conference Proceedings
A distributed IoT system for modelling dynamics in smart environments	2020	Serbia	Journal Article
Smart cities with digital twin systems for disaster management	2020	USA	Journal Article
Social sensing in disaster city digital twin: Integrated textual-visual-geo framework for situational awareness during built environment disruptions	2020	USA	Journal Article
Digital geotwin Vienna: Towards a digital twin city as geodata hub	2020	Austria	Journal Article
Cognition digital twins for personalized information systems of smart cities: Proof of concept	2020	USA	Journal Article

Table 2. *Cont.*

Title	Year	Country	Type of Publication
An ISO/IEEE 11,073 standardized digital twin framework for health and well-being in smart cities	2020	Canada	Journal Article
From LiDAR point cloud towards digital twin city: Clustering city objects based on Gestalt principles	2020	Hong Kong	Journal Article
Architecting smart city digital twins: Combined semantic model and machine learning approach	2020	USA	Journal Article
Automatic 3d buildings compact reconstruction from LiDAR point clouds	2020	Belgium	Conference Proceedings
Smart city development with digital twin technology	2020	Finland	Conference Proceedings
Research on the construction of smart city emergency management system under digital twin technology: Taking the practice of new coronary pneumonia joint prevention and control as an example	2020	China	Conference Proceedings
Exploring the opportunities of open source data use in creation 3d procedural city models	2020	Turkey	Conference Proceedings
Urban digital twins for smart cities and citizens: The case study of Herrenberg, Germany	2020	Germany/ Netherlands	Journal Article
The digital twin of the city of Zurich for urban planning	2020	Switzerland	Journal Article
Digital twin modeling of smart cities	2020	Bulgaria	Journal Article

The published work related to the city digital twin was thematically analyzed to identify the current research directions, classify the benefits, and signal current and expected challenges regarding utilizing a digital twin in city modeling and smarting the city. Thematic analysis is a flexible method that helps find patterns in textual data, primarily if the data set is determined, and to inductively explore the data and draw conclusions [30,31]. This makes thematic analysis suitable for reviewing the literature, identifying its main themes, and extracting research gaps. Braun and Clarke suggested six phases for a rigorous thematic analysis: familiarizing with data, generating initial codes, searching for themes, reviewing themes, defining themes, and producing the analysis outcome [32]. Following the six-phase approach, the data were reviewed and coded, while themes were elaborated iteratively. Finally, five themes were identified to organize and describe the city digital twin's current and prospective potentials and challenges.

4. Thematic Identification of the City Digital Twin Potentials

The thematic analysis of the city digital twin articles identified five themes: data management, visualization, situational awareness, planning and prediction, and integration and collaboration (Table 3). Through these themes, the achieved and perceived potentials and use-cases of utilizing the city digital twin can be comprehended, and, subsequently, a research agenda can be proposed to maximize the benefits of the city digital twin further.

Table 3. Themes regarding the potentials of the city digital twin.

Themes	Applications	Articles
Data Management	- Data processing - Interoperability - Software fusion - Open-source software	[33–47]
Visualization	- Navigation - 3D real-time experience - Multi-spatial and temporal scales - Unified platform - Behavior modeling - Network dynamics - Personalized information systems	[27,37,40–43,48–54]
Situational Awareness	- Monitoring - Tracking - Localization - Face recognition - Analysis	[33,34,40,42,50,55–69]
Planning and Prediction	- Policy evaluation - Simulation - "What if" scenarios	[13,27,40,42,46,56,66]
Integration and Collaboration	- Multiple domains integration - Stakeholders' participation - Citizens' engagement - Open platforms	[13,27,34,37,40,46,56,61,63, 66,70–72]

4.1. Data Management

Data management represents the first and core theme of the city digital twin. Due to the city's several dimensions and the vast amounts of heterogeneous data that can be generated and collected from the city, the ability to manage and process city data is substantial. To solve heterogeneous data, utilization of the ontological approach was suggested to improve the semantic interoperability and secure future data expansions [35–37]. Developing multi-layered system architecture for the city's digital models was also proposed to manage and integrate various data types in the digital twin model [34,45]. In addition, although the underground infrastructure data lack appropriate levels of accessibility and quality, it was suggested that they are candidates for better interoperability due to the ability to integrate several data models [44]. Nevertheless, the large amount of data generated from city operations constitutes an issue in handling and operating digital twins, especially on the city scale. Thus, Nys, Billen, and Poux attempted to reduce the size of the 3D model and lower the time consumption in generating the model by utilizing faster, lighter, and more readable data formats, but their model's low level of details (LOD) and the generated geometrical failures pose some challenges [47].

To control the size of the digital twin's data stores and minimize errors in the model, it was suggested to use procedural techniques in the 3D modeling of the city [38]. In addition, Austin et al. (2020) pointed out the benefits of combining machine learning techniques with semantic modeling to better handle large-sized and heterogeneous data [33]. While generating a model for the city scale is time-consuming, Xue et al. proposed a method to reduce the time of developing the model out of LiDAR point clouds, but their method cannot be processed on unsymmetric objects, in addition to having geometric errors [39]. Utilizing point clouds for modeling conveys both potentials and challenges. For example, it provides representations of irregular objects but without topological linkage. In addition, the point cloud redundancy facilitates data processing, compression, and storage [41]. Dou et al. developed a spatiotemporal big data visualization platform that utilizes the fusion

of GIS and BIM to process, analyze, integrate, and visualize the multi-source data of the city [42]. Furthermore, by linking the model with several data sets for building a city information model, temporal coherent raw geodata was produced [43]. Democratizing urban data is perceived as an essential issue to secure access to city data through the citizens' digital twin. Dembski et al. utilized open-source software to provide the citizens and professionals of the city the opportunity to participate in the city digital twin's evaluation and development through data and software availability [40].

Several potentials and advancements have already been obtained by the city digital twin regarding data management, yet some challenges are still hindering the full utilization of its benefits. For instance, to process and integrate various city domains' heterogeneous data, data standardization and data-sharing frameworks for improving data exchange among software applications are major challenges [37,46].

4.2. Visualization

The primary role in city modeling is enhancing the visualizations of the city. Improved visualization can bring about a better understanding of the urban environment and a reduction of errors in design. The digital twin capability of utilizing and integrating with other modeling and visualizing applications promotes the digital twin's visual experience. For instance, visual navigation through the city with different perspectives and scales was developed by utilizing VR and augmented reality (AR) technologies [51], while a VR visualization of the city linked with environmental and other urban analysis data at a full-size scale was demonstrated [40]. Medeiros presented an enhanced spatial under-standing and navigation for urban digital twins through an immersive VR application [52]. In addition, street spaces, infrastructure, high-rise buildings, and BIM models can be ex-perienced digitally by navigation via an Internet portal [27], while an urban simulation platform was developed to display a 3D real-time updated model showing the queries and analysis of various city domains [42]. Moreover, for enhancing visualization of the city digital twin model, several developments were exercised, for instance, incorporating various city elements such as terrains and dynamic vegetations [53,54], visualizing both existing and planned built environments [37], visualizing the city with multidimensional and multispatial scales [40,42], utilizing point clouds to limitlessly model any object in the city [41], and using several LODs in the digital twin model to extract the suitable one according to the application [43].

Visualizing social systems is among the main challenges in developing a visibly enhanced city digital twin. However, some research has been conducted to address that challenge. For instance, an approach for behavior modeling based on meeting agents' needs using a set of behavioral patterns was proposed [49]. Furthermore, a mathematical model for integrating active agents' mental features into digital twins was developed [48]. Furthermore, Fan et al. proposed using dynamic network analysis for visualizing network dynamics within a disaster in a city digital twin [50].

4.3. Situational Awareness

The city digital twin is anticipated to construct a link with the real city or the physical counterpart to enhance the visibility of the city and the understanding and analysis of the city's events and operations. For that purpose, the city digital twin is perceived as enabling technology to promote situational awareness for city management and to provide a city information model; that is, the city digital twin can collect, monitor, and manage city data [34]. For instance, it can reflect citizens' health condition [58]; represent, reason, and analyze energy consumption data [33,55,65]; detect motion for public security activities [42]; monitor noise pollution in the city using dynamics modeling [61]; provide real-time tracking of information during disasters and localize vulnerable objects [50,56]; and track and monitor individuals' behavior and localize disruptions and potential risks for emergency and disaster management [57,64,68]. It is also anticipated to enhance risk analysis and prevention and identify information flows for disaster management [60,69].

While analyzing city functions, several applications were proposed, such as providing urban and street network space syntax analysis and movement patterns [40,66], understanding commuting patterns [63], comparing and analyzing citizens' needs for urban services [62], and urban spatial and traffic congestion analysis [42]. Furthermore, some attempts were made to develop more human-centered digital twins, such as suggesting a method to personalize information systems by modeling cognitive reactions to different types of information [67]. In addition, Lee et al. proposed utilizing biosensors to monitor and spatially detect elders' stressful interactions with the city in their trajectories to identify the risky spots in the city and provide safer alternative routes. However, the research about monitoring individual stresses lacks identification of the different levels of stress, which requires further investigations.

The city digital twin is providing viable contributions in perceiving different states of the city on multispatial and temporal scales, and in several domains such as health care, energy management, disaster management, emergency response, mobility, and urban planning.

4.4. Planning and Prediction

Past and present objects and processes in the city can be well-captured by the city digital twin model and can be further analyzed to better understand how the city operates. Nevertheless, the digital twin's main advantage is providing useful insights about future patterns and plans. Prediction of the physical twin's future behavior to optimize its performance has been highlighted in other fields, such as aerospace and manufacturing. Similarly, for the city digital twin, developing possible plans and future city operations scenarios to optimize how the city functions can be a significant benefit.

However, some research has been conducted to support decision-making processes and promote alternative policy scenarios. For instance, Dembski et al. developed traffic scenarios and air pollution simulations to test their urban planning impact [66]. Nochta et al. illustrated the evaluation of different scenarios of electric vehicles' charging locations and the cross-sectoral impacts through the city digital twin [46]. Other applications were experimented with for supporting decision-making by providing "what if" scenarios for several domains of the city. For instance, simulating possible physical objects' failures in the city via participatory sensing was insightful for improved risk management [56]. Urban development plans and urban climate scenarios and simulations were tested to support urban planning decision-making [27]. Several other planning and prediction applications linked to the digital twin were found useful, such as flooding scenario analysis [42], evaluating solar energy potential and wind flow impact on the built environment through simulations of weather changes [13], and urban mobility simulations [40].

4.5. Integration and Collaboration

The complexity of the city, the interdependencies between its elements (such as humans, infrastructure, and technologies), and the relatedness among its domains portray the challenge of integrating the information of all these spheres in one platform and providing a collaborative environment for the co-creating and co-development of the city digital twin. The integration of the city digital twin can be seen through two dimensions. The first is the 3D model itself, and for addressing that, Wan et al. argued that developing several digital twins for the city may be more feasible than developing one model for the whole city's systems and processes [63]. Castelli et al. suggested organizing the city digital twin into layers to integrate the city's various domains and dimensions [34]. In addition, Radenkovic et al. pointed out the availability of using "loosely coupled" models to overcome the complexity of the physical counterpart and its multiple domains [61].

The second dimension is the provision of a collaborative environment among the various stakeholders of the city. Utilizing online and open platforms enables data sharing and promotes stakeholders' inclusion in city planning and policy design and evaluation [13]. It is highlighted that digital twins can engage the citizens in creating new plans for the city

and enhancing public decision-making [37,66]. Furthermore, by assigning different levels of authorization, the city digital twin can be accessible, navigated, and discussed by the public for urban planning purposes [27]. A good deal of research pointed out the potential of constructing linkages among the stakeholders of different city domains and the benefits from citizens' engagement via the digital twin [40,46,56,63,70–72].

5. Challenges to the Full Utilization of City Digital Twin Potentials

In addition to identifying the potentials of the city digital twin, reviewing the literature showed several challenges that are still hindering the full utilization of digital twins on the city scale. Following the five themes of the city digital twin through which the potentials were comprehended, we can demonstrate the main challenges and thus identify the gaps in the literature to draw a research agenda for future research.

In data management, for instance, one of the biggest concerns is the large-sized, complex, and heterogeneous nature of the city data [13,33,35,39,59]. In light of that, data acquisition and processing are threatened by the requirements of higher levels of computing powers and interoperability among the huge and various sets of data. Furthermore, the size and complexity of the city data shed a light on the necessity of developing widely accepted standards for the data models and design schemas [27,37] to facilitate the development of the city models, in addition to gaining its benefits in reducing time, cost, and errors. Furthermore, data accessibility can be challenging due to ownership and expensiveness [44,68].

Visualizing the city scale in the digital twin is still lacking the comprehensiveness of the city information [66]. Several digital twin cities were developed that lack model accuracy, completeness, and graphical representation qualities [34,39,40,47]. In addition, utilizing participatory sensing and crowdsourced data to supplement limitations of sensory information revealed some localization errors and untrusted data [38,56,57]. The inaccuracy and errors of modeling affect not only the visual experience but also the situational awareness of the city. Notwithstanding, a critical drawback in being aware of the city's as-is condition is the lack of awareness of the contextual factors and the non-physical systems such as social, economic, and political structures and processes, in addition to the interactions among people, infrastructure, and technology [56,63,69,71,72]. In addition, inadequate situational awareness would challenge the quality of planning and prediction capabilities of the digital twin. That is, the incompleteness of the city model, whether due to lack of accurate data or how it is visualized [38,46], will affect the city digital twin's ability to provide useful planning decisions or predictions of future scenarios.

Furthermore, developing a complete city digital twin requires high levels of integration due to the various city domains and information. The city digital twin model is anticipated to provide insights about all city systems and processes that produce different types of data with different formats among different sectors and stakeholders. Thus, developing more enriched semantic information [47], understanding and modeling system interactions [69], and identifying requirements for interoperability among the various systems [45] are required for further development of the city digital twin model. In addition, the need for engaging the public and the different sectors of the city and providing accessibility to the model is still challenging due to several issues related to lack of governance structures, data-sharing frameworks, and participants readiness, awareness, and willingness [40,46,64]. In addition, enhancement of the integration and collaboration qualities of the city digital twin implies societal challenges that need to be investigated, such as privacy and security issues [33,35,69].

The challenges to fully utilize the city digital twin potentials that have been comprehended from the literature highlight the necessity of further research and development toward enhancing data management and standardization of data models for improved data interoperability and processing. Furthermore, it is demonstrated that the developed city digital twin models are not yet complete nor comprehensive due to several drawbacks, such as the lack of accuracy, the occurrence of errors, and lack of integration of human interactions and socio-economic and political factors. However, other threats are foresee-

able as implications to developing complete and comprehensive digital twin cities, such as citizens' privacy and data security issues.

6. Discussion and Research Agenda

One major benefit of the city digital twin is connecting past and present information and future scenarios. The ability to integrate several data models across time and space and present the information on a single 3D model enriches the exploration, understanding, and foreseeing of current and future trends of the city's operations. The thematic analysis revealed the exercised potentials of developing a city digital twin on almost all the city domains. The development of digital twin cities is already contributing to enhancing city management, functions, and operations. Currently, the level of development that has been reached so far can improve city data management, digital visualization of the city, awareness of several spatiotemporal situations, predictions of future scenarios, and integration of the city domains and stakeholders (Figure 2). Some of the research reviewed in this paper proposed theoretical frameworks or system architectures to develop digital twin cities. However, a good deal of practical research showed notable advancements in digital twin cities' usability in enhancing city operability and management. Although city digital twin research is still in its infancy, with robust research linking digital twins to city-scale modeling starting very recently, it shows a rapid pace of development towards fully utilizing digital twin technology in the advancement of cities.
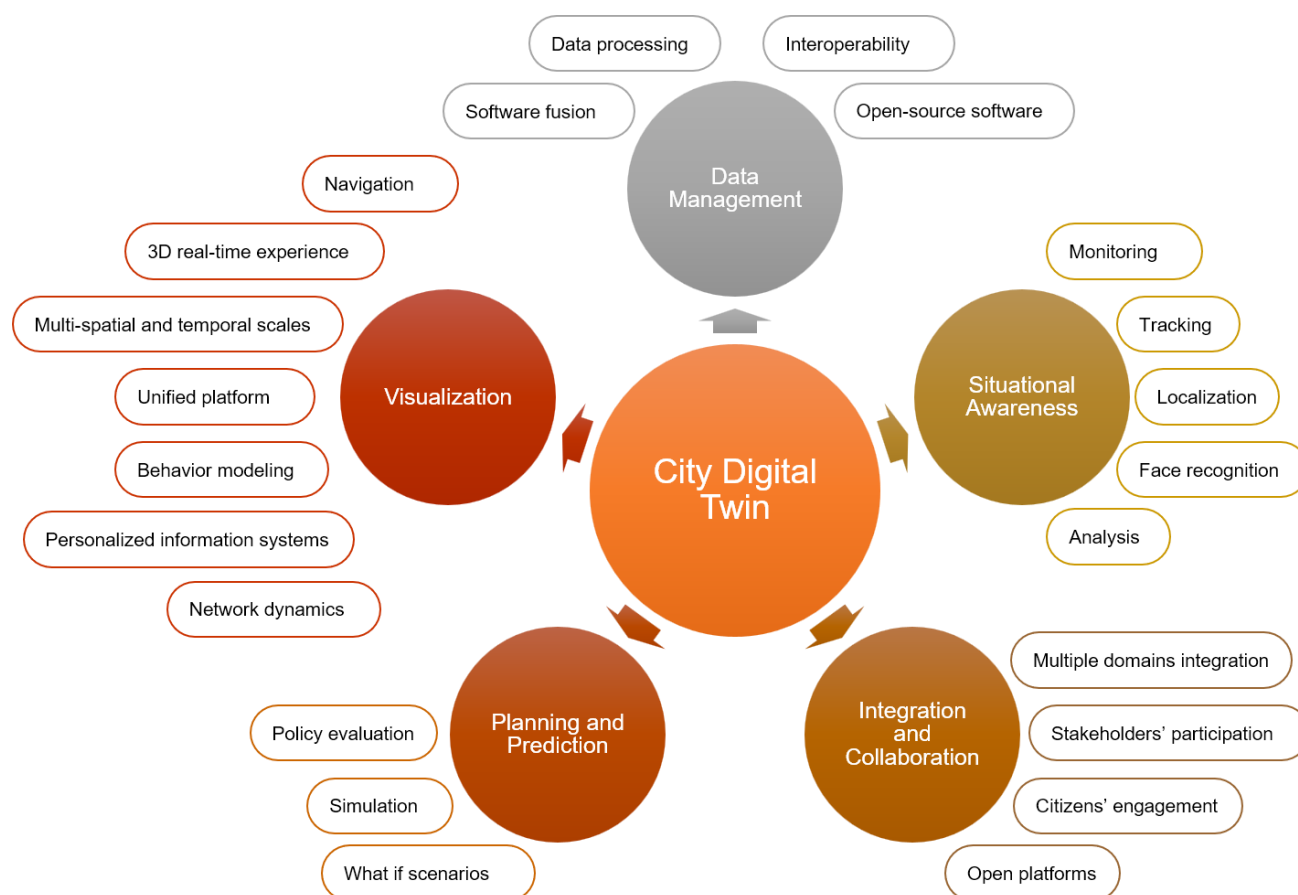

Figure 2. City digital twin potentials.

Deriving from the review and thematic categorization of the city digital twin research, the gaps and the main challenges to achieving a wholly mirrored city digital twin were comprehended. For instance, although several approaches had been proposed to develop an integrated and unified data model for the city digital twin, the literature lacks a concrete

application of such a model that presents the full utilization of a comprehensive city digital twin that uses standardized and unified data schemas, and is thus capable of including all city functions and processes. The visualization of the city's full physical details is still lacking due to the tremendous number of details required to fully represent the city in the digital model, which requires high capacities to handle and process the large-sized digital model. Furthermore, visualizing the non-physical systems and human interactions is a significant challenge, although socio-economic activities are substantial in the city realm. Furthermore, in the city digital twin literature, the current technology developed focuses on the transfer of information from the physical to the digital counterpart, while fully utilizing the capabilities of the digital twin technology requires mutual integration between the two counterparts, which is not well addressed in the literature.

In addition to the previously mentioned digital twin example of the city of Zurich, another notable example is Virtual Singapore. They developed a city digital twin through the Virtual Singapore program, where the idea was to synergize all the 3D efforts into a unified platform for a more collaborative environment for all public agencies, in addition to citizens, the private sector, and research institutions [73]. The model facilitates better visualization of the city/state, real-time collection of information and analysis, and simulations and "what if" scenarios for enhanced planning and decision-making. It can be perceived as a very significant city digital twin. Still, it did not reach the level of a complete digital twin since, for example, the flow of information is still one-way from the physical side to the digital.

However, future research on developing the city digital twin is required to focus on the areas that may advance the current technology and reach a completely mirrored digital twin level. Batty argued that a completely mirrored digital twin could never be achieved [14]. Yet, he assured that the efforts to make the digital model as close as possible to its physical counterpart are necessary. In addition, he highlighted the inclusion of the city's social and economic components as the main challenge to achieving a complete replica of the real city. However, although it seems almost impossible to achieve a digital twin that mirrors the full details of the city's physical, social, and economic aspects, the research community is bound to investigate all possible means to advance the technological tools and uses for enhancing the city digital twin for better visualization, realization, and management of the city. Thus, identifying the potentials and challenges of creating digital twin cities was necessary to develop a research agenda that may contribute to the further development of digital twin cities.

Following are the three main research directions, which constitute a research agenda that can guide city digital twin researchers, city managers, and developers to focus and intensify their efforts towards developing a comprehensive and completely mirrored city digital twin.

6.1. Enhancing the Efficiency of Data Acquisition and Processing

Enhancing data management in the city digital twin will always be open for further research. Data management is the core element in obtaining a city digital twin, and the level of data quality and accuracy is decisive in developing an efficient and effective digital platform for the city. Although promising advancements took place in data transfer, storage, and processing, some challenges are still hindering the full utilization of the city digital twin's capabilities as a unified platform. Among the main challenges is data standardization, in which the generated heterogeneous data and the various domains of the city that require the fusion of several software applications point out the necessity of developing data standards for the city digital twin.

Some research proposed the standardization of their data models or the utilization of open standards, which are not widely used yet. However, they cannot be generalized due to the diverse methods and software used in the city digital twin and the ongoing emerging technologies and data generated within the city domains [37,42,58,60]. Generalized data standards will facilitate data management and interoperability among the various domains

and software and promote further research in several contexts. Furthermore, for a complete and comprehensive model, the LOD of the city model requires further research because the more details the 3D model provides for enhanced visualization, the more extensive the size will be. The enlargement of the model will lead to difficulties in processing; that is, there is a trade-off between having higher LOD to better visualize the city digital twin from one side, and the size of the model on the other side, which is required to be as small as possible to better handle the data, and thus fully utilize it for analyses, predictions, and further applications.

6.2. Promoting the Integration of Socio-Economic Components

As a complex system of systems, the city requires a complex model representing its diverse systems and domains. The integration of non-physical systems, such as socio-economic processes or activities, is among the highest challenges in visualizing and realizing the complex city system. Some studies have addressed some aspects of including these non-physical components in the city digital twin model, such as behavior modeling according to agents' needs and mental features [48,49]. Others investigated monitoring citizens' health conditions, movement patterns, and stress detection for the elders [40,58,59]; that is, placing the human factor at the center of the digital twin is gaining research attention. Yet, many applications can be anticipated from integrating the non-physical components that can enhance several city domains such as urban planning, mobility, and the environment.

The improved modeling of socio-economic behavior and activities in addition to considering the contextual factors such as political settings, governance structures, and culture will provide better insights in understanding the city and performing more in-depth analysis and future scenarios simulations, which, in turn, will improve planning and decision-making. However, the challenges are extended from data collection and modeling to other privacy and data security issues. The authorities' access to personal data will jeopardize public privacy, which requires serious and transparent dialogue with citizens. Furthermore, personal data leakage by third parties or hackers will pose a critical threat. In addition to investigating how one can model these non-physical components, the foreseeable impacts of including them in the digital twin model are of no less importance.

6.3. Developing Mutual Integration between the Digital and Physical Counterparts

Although it is not pointed out in the reviewed literature, a crucial part of achieving a wholly mirrored city digital twin is its mutual integration with the physical counterpart. The ability to update the digital twin by receiving information in real-time or near real-time from its physical counterpart is already proven. However, the inverse direction of data transfer, and thus control over the city's physical side, is still challenging. As previously mentioned, in the manufacturing field, Kritzinger et al. drew lines among the digital model, digital shadow, and digital twin [11]. The data flow between the two counterparts is manual in the digital model, and automatic from the physical entity to the digital entity in the digital shadow. In contrast, the data flow is automatic in two directions in the digital twin. That is, the mutual interaction between the digital and physical counterparts that occurs in the digital twin is not achieved yet in any developed city digital twin. Thus, what one calls a city digital twin should be called a city's digital shadow, as it is not fulfilling the main attribute of the complete digital twin, which is the full integration between the two counterparts.

Developing a mutual integration between the two counterparts means that the digital twin model can have control commands over the physical counterpart. Thus, it may contribute to improving city management, for instance, by enhancing urban efficiency and the delivery of services. To control the physical counterpart, using artificial intelligence and actuators to give feedback to the physical counterpart was suggested [58]; this may be achieved in a few dimensions, such as energy management and construction [27,65], but it remains under research for the larger scale of the city. In addition to utilizing artificial intelligence, building on the research in robotics and automation is axiomatic when one con-

siders the full integration of the city's digital twin and the advancement of control features for optimizing city management and operations. Notwithstanding, careful consideration of the threats that may be brought about by enhancing city management and operations automation, such as urban segregation and regulatory challenges, is imperative [74].

The proposed future research directions are intended to widen the potentials of the city digital twin by adding another theme that will need further research, which is the ability to control the physical side of the city via the digital model (Figure 3). Besides, going forward with this research agenda is anticipated to enhance the current potentials of the city digital twin towards achieving the development of a wholly mirrored city digital twin, especially if the research addresses the city digital twin as a whole, and so, the interrelationships between its potentials can be realized, and a more holistic view of its contribution to the enhancement of the city's operability and management can be achieved.

Figure 3. Advancement of the city digital twin's potentials.

7. Conclusions

The wholly mirrored city digital twin that replicates the physical reality has not been developed nor fully understood yet. However, the pace of development of the city digital twin is relatively fast and is expected to provide higher potential for city management and to raise the quality of life of its citizens. Although the city digital twin will not provide solutions for all city problems [63], previous research is diverse and shows several benefits to utilizing digital twin cities across the city domains.

To maximize the potentials of the city digital twin, research efforts should focus on enhancing the efficiency of data processing, promoting the inclusion of the city's socio-economic components, and developing a mutual integration among the two counterparts of the city digital twin. The intensification of research efforts on the three recommended areas

of the research agenda for advancing the current city digital twin will not only enhance the operability of the digital model, by raising its data processing efficiency and providing a higher visualization experience; it can also promote deeper situational awareness of the city processes and activities, due to enhanced data collection and the inclusion of additional components of the city that are lacking in the current city digital twin. The potential of simulating future scenarios for supporting decision-making and predictions will be better informed by further data that is essential for improving its predictability. Although obtaining the information from the physical counterpart has been developed to be in real-time, using sensors and IoT technologies, which enhance understanding of the city, developing mutual integration between the two counterparts will create wider opportunities in raising the efficiency and efficacy of the city operations by minimizing human interference, and thus reducing errors and optimizing the delivery of services. This mutual integration can expand the city digital twin's usability by taking advantage of the digital model to visually experience and support decision-making to control the physical counterpart further, and thus optimize the city management.

In a practical sense, enhancing the efficiency of data processing would facilitate utilizing a large-scale model that covers the whole city with higher levels of detail. An improved experience of visualizing the city through the digital model would be anticipated, which will support urban planners in understanding the city and thus adjusting plans to the reality of the city. Furthermore, instead of having sets of data of limited sections or buildings (about energy consumption, for instance), the information would be available for the whole city, and thus better policies could be adopted according to the analysis of consumption patterns, leading to more efficient energy management policies. Integrating and visualizing socio-economic components of the city would enhance the realization of public social and economic behavior in general, and would provide deeper insights into public patterns of movement, activities, and expectations. This would promote urban planning development plans that conform to citizens' needs. For instance, understanding people's movement patterns will affect transportation planning and operations, making them more efficient and service-oriented. Advancing mutual integration between the digital and physical counterparts would bring about enormous benefits to the city's operation and management. Controlling traffic systems and dynamic road and congestion pricing are examples of optimizing city operations that would be better informed by real-time updated traffic data in the digital twin and the use of machine learning and artificial intelligence analytical tools. Another implication is the possibility of controlling operations of energy consumption at the city scale, for instance, in public spaces and with streetlights. However, more research is required to explore the possible implications of the complete city digital twin in the various domains of the city, such as construction, health, and education. In other words, the completely mirrored city digital twin is anticipated to accurately reflect and affect the city's functions and processes to enhance its realization, operability, and management.

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