The uptake of City Information Modelling (CIM): a comprehensive review of current implementations, challenges and future outlook

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Abstract

Purpose – This paper critically analysed 195 articles with the objectives of providing a clear understanding of the current City Information Modelling (CIM) implementations, identifying the main challenges hampering the uptake of CIM and providing recommendations for the future development of CIM.

Design/methodology/approach – This paper adopts the PRISMA method in order to perform the systematic literature review.

Findings – The results identified nine domains of CIM implementation including (1) natural disaster management, (2) urban building energy modelling, (3) urban facility management, (4) urban infrastructure management, (5) land administration systems, (6) improvement of urban microclimates, (7) development of digital twin and smart cities, (8) improvement of social engagement and (9) urban landscaping design. Further, eight challenges were identified that hinder the widespread employment of CIM including (1) reluctance towards CIM application, (2) data quality, (3) computing resources and storage inefficiency, (4) data integration between BIM and GIS and interoperability, (5) establishing a standardised workflow for CIM implementation, (6) synergy between all parties involved, (7) cybersecurity and intellectual property and (8) data management.

Originality/value – This is the first paper of its kind that provides a holistic understanding of the current implementation of CIM. The outcomes will benefit multiple target groups. First, urban planners and designers will be supplied with a status-quo understanding of CIM implementations. Second, this research introduces possibilities of CIM deployment for the governance of cities; hence the outcomes can be useful for policymakers. Lastly, the scientific community can use the findings of this study as a reference point to gain a comprehensive understanding of the field and contribute to the future development of CIM.

Keywords City information modelling, Urban management, 3D city model, Smart city, GIS, Cities

Paper type General review

1. Background

The City Information Modelling (CIM) has gained momentum over the last decade due to its capacity to improve planning and designing practices in the urban environment (Souza and Bueno, 2022; Xue *et al.*, 2021; Xu *et al.*, 2014, 2021). CIM adopts various computer-centric technologies to represent urban systems and elements in 2- or 3-dimension (D) formats (Xue *et al.*, 2021). Several definitions are presented in the literature to describe the concept of CIM. As tabulated in Table 1, the concept of CIM has a proximity to the Geographic Information System (GIS), a computer-based system application that captures, analyses and geographically visualises referenced data about the Earth's surfaces (Xue *et al.*, 2021; Xu *et al.*, 2014). Stojanovski (2013) described CIM as an analogy to BIM in the context of cities,

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References	Definitions	Characteristics of CIM
Dantas *et al.* (2019)	"CIM represents a superior level of infrastructure, network, administration and human activity. This model facilitates visualizing, analysing and monitoring the urban environment in order to support project and planning from local to regional overview. Hence, CIM is characterized by a multidisciplinary unification of all spatial data model" (p. 2)	• CIM supports planning in urban environments • Its multidisciplinary nature • Relies on using spatial data received from BIM models
Xu *et al.* (2021)	CIM represents a 3D model of a city based on information collected, stored and processed via technologies such as Internet of Things (IoT), BIM and GIS for urban planning purposes	• The use of technologies such as IoT, BIM and GIS to obtain data • Urban planning
Xu *et al.* (2014)	CIM is a platform established by integrating data received from BIM and GIS models, which leads to increasing the efficiency of city management	• Using GIS and BIM data models • Urban management
Wang and Tian (2021, March)	CIM establishes "an organic synthesis of a three-dimensional urban spatial model and urban information" using data obtained via BIM, GIS and IoT (p. 1)	• CIM relies on data received from BIM, GIS and IoT
Gil *et al.* (2011)	The CIM is a design support tool in urban planning, developed based on extending the use of GIS and integrating such an application with CAD (Computer Aided Design)	• CIM adopts GIS and CAD. • CIM is a decision-making tool in urban planning

Table 1.
Definitions of CIM

encompassing urban elements such as spaces, activities and communications that are represented in 2D and 3D. Further, Stojanovski (2013) characterised CIM as a 3D extension of GIS equipped with multilevel and multiscale views, a toolbox for designers and a database of 3D items. Julin *et al.* (2018) also mentioned that 3D models of cities can be constructed by superimposing photogrammetry and laser scanning data with GIS data. Notwithstanding the similarities, the core concepts of CIM and GIS are fundamentally different. The distinction relates to the entity of "I", e.g. information. In GIS, the information is often managed in the form of layers and it is usually referenced in accordance with the scope of the Earth's surface (Xue *et al.*, 2021). Contrarily, CIM concentrates mainly on the urban areas while taking into account non-GIS data such as building information modelling (BIM), Light Detection and Ranging (LiDAR) technology, city energy modelling, or residents' behaviours and it is managed in the form of cross-reference relation networks—akin to BIM (Xue *et al.*, 2021; Xu *et al.*, 2014; Liu *et al.*, 2017).

In the approach of using GIS to build CIMs, buildings are roughly represented through prisms or boxes without presenting detailed information on the as-is conditions. As a result, a new trend has emerged with the advancements in data acquisition and processing technologies (e.g. Big Data, Artificial Intelligence (AI), Data Mining and Data Fusion) in that detailed geometric features of rooftop objects are reconstructed by employing BIMs. Hence, the concepts of BIM and CIM have begun to appear together. For instance, studies defined CIM as a system that integrates a set of technologies such as GIS, BIM, IoT and data acquisition and processing techniques to represent an accurate virtual image of cities (Montenegro and Duarte, 2009). However, the concepts of BIM and CIM are different, thus it is important to differentiate their characteristics. The main difference stems from the scope of the keyword "information". BIM utilises building-level information (e.g. building geometry, building materials, building orientation) to represent a building's embodiment and its associated components (e.g. external walls) (Xue *et al.*, 2021; Karan *et al.*, 2016). The data relating to geometric, semantic and topological attributes of buildings are also distinguished by the taxonomy of information entities in BIM (Xue *et al.*, 2021). The geometric data correspond to the shapes and forms of buildings and their components, whereas semantic information entails intrinsic properties (e.g. functionality) (Xue *et al.*, 2021). The topological information also establishes the associations between modelled objects (Xue *et al.*, 2021). CIM, on the other hand, is a 3D representation of elements within the urban scale that links buildings to other sources of information (e.g. urban infrastructure, city facilities, etc.) in a city (Xu *et al.*, 2014). Hence, a well-developed CIM contains comprehensive data representing urban spatial configurations and provides virtual demonstrations of objects situated in cities.

Nowadays, the extent of CIM applications is stretched from assisting urban planners in designing sustainable cities (Khemlani, 2016; Souza and Bueno, 2022) to the governance of cities (Souza and Bueno, 2022; Chen *et al.*, 2018) or facilitating the operation of location-based services at the individual citizen level, e.g. transportation navigation, emergency response, etc (Chen *et al.*, 2018). Recent research also endeavoured to integrate advanced technologies such as AI, cloud computing, big data and virtual reality with CIMs towards the development of smart cities (Jamei *et al.*, 2017; Peng *et al.*, 2019). This indicates that the intellectual basis of CIM is multifaceted with many areas of research being increasingly intersected with this concept across many disciplines. In this regard, a few studies (Souza and Bueno, 2022; Xue *et al.*, 2021; Xu *et al.*, 2021) have provided reviews on different aspects of CIM such as simulation methods and workflows of urban building energy models (Ang *et al.*, 2020; Reinhart and Davila, 2016), the semantic enrichment of CIM (Xue *et al.*, 2021), investigating possibilities for integration of GIS and CIM (Liu *et al.*, 2017; Xu *et al.*, 2014) and the use of CIM as a decision support approach for improvement of management practices in urban planning (Souza and Bueno, 2022). Nevertheless, there is a lack of understanding about the extent of CIM implementations in urban environments. This highlights the necessity of developing a study to consolidate the current knowledge by providing a holistic overview of CIM implementations in the built environment.

Therefore, this paper approaches the literature with the objectives of (1) providing a clear understanding of the current CIM implementations in the built environment, (2) identifying the main challenges hampering the uptake of CIM and (3) providing recommendations for future development of CIM. The outcomes of this research are beneficial for different target communities. First, urban planners and designers will be supplied with a status-quo understanding of CIMs being implemented for designing urban environments. Second, this research also introduces possibilities of CIM deployment for the governance of cities, hence the outcomes can be useful for policymakers. Lastly, this paper singles out potential directions for future development of CIMs, thus the scientific community can use the findings of this study as a reference point to gain a better understanding of the field and contribute to the future development of CIM.

2. Research approach

This study adopts Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) in order to perform the systematic literature review. The PRISMA introduces an evidence-based framework that can be used as a basis for conducting systematic reviews (PRISMA, 2022). The use of PRISMA can improve the quality of systematic reviews and meta-analyses by enabling researchers to formulate roadmaps for conducting a research prior to its completion (Moher *et al.*, 2009). This approach has been widely utilised by studies related to urban planning and management (Bueno *et al.*, 2021; Geekiyanage *et al.*, 2020). Figure 1 illustrates the four main stages, namely (1) identification, (2) screening, (3) eligibility and (4) inclusion involved in carrying out the searching exercise.

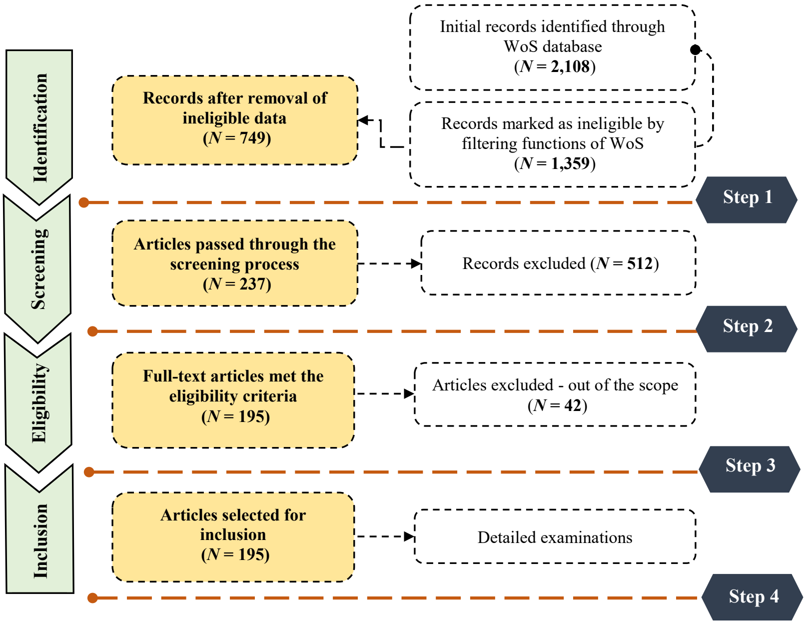


Figure 1.
Illustration of research approach based on PRISMA

The first step was the identification in which materials corresponding to the aim of this study were searched. In this stage, selecting a database for the retrieval of publications is of grave importance due to the direct influence of databases on the quality of results. To date, several bibliometric sources are available including Scopus, Web of Science (WoS), Medline, ScienceDirect and Google Scholar. The coverage of these databases differs, hence influencing the search results when it comes to research disciplines. Among all, the WoS is one of the most commonly used databases for performing literature review analysis because of its unique features that provide access to over 171 million records in 34,000 journals and over 1.9 billion cited references across many disciplines (Web of Science, 2022). As such, this study selected WoS for finding publication data due to its scientific soundness and comprehensiveness.

Thereafter, a search syntax was designed to comprehensively capture studies related to the CIM applications using keywords "Information Model*" OR "CIM*". These terms were then combined with "Cit*" OR "Urban" OR "Smart Cit*" OR "Digital Twin*" OR "Urban Management" OR "Urban Plan*" OR "Urban Data" OR "3D City Model" OR "Geographical Information System" using Booleans ("AND"). This search matrix was then utilised as the search query in the WoS database to obtain relevant data.

The search was carried out using the titles, abstracts and keywords of publication materials within the Web of Science Core Collection (including Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Emerging Sources Citation Index (ESCI), Conference Proceedings Citation Index- Social Science and Humanities (CPCI-SSH), Conference Proceedings Citation Index- Science (CPCI-S) and Arts and Humanities Citation Index (A&HCI)) database indexed since 1900. This search returned 2,108 documents on the 11th of March 2022 including 1,395 articles, 497 proceeding conferences, 143 review articles, 32 early access, 14 editorial materials, 7 book reviews, 5 meeting abstracts, 5 notes, 3 corrections, 3 letters, 3 new items and 1 biographical item. Prior to initiating the screening stage, three filters were applied to remove irrelevant materials using filtering functions of WoS. First, the search only included “articles”, “review articles” and “book chapters” owing to the reputability of these sources (Omrany *et al.*, 2022a). Second, only publications written in English were retained for further analyses. Third, resources unrelated to the CIM application (e.g. fisheries, entomology, pharmacology, medical and agricultural sciences) were filtered. Considering these filters led to downsizing the database to 749 publications.

The second step was “screening” in which publications shortlisted through the preceding stage were qualitatively checked by analysing their titles and abstracts. In this stage, only studies that applied computer-based technologies for modelling urban elements and systems within the contexts of cities were selected for further examinations. As a result, 512 studies were excluded. In the third step, the eligibility of selected publications was evaluated by reading their full texts to assure their perfect alignments with the scope of this study; thus, 42 more publications were phased out. Finally, 195 studies were selected for detailed examination in the fourth step.

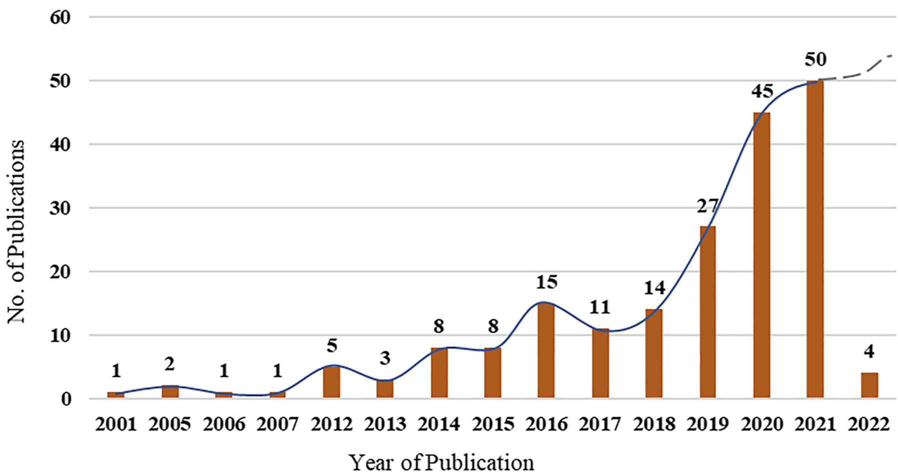
3. Results and analysis

This section begins by providing an overview of the 195 selected materials with the goal of understanding the current state and evolutionary progression of the knowledge. The analyses include the yearly trend of publication and geographical distribution. This follows by critically discussing the current trend of CIM implementations in the field.

3.1 An overview of the literature

Figure 2 illustrates the yearly trend of publications with a focus on CIM implementation in the built environment. The first identified paper was published in 2001, discussing the importance of preserving historical and heritage buildings in contemporary urban management (Elkadi and Pendlebury, 2001). Elkadi and Pendlebury (2001) recommended the development of an information model integrated with a relational database and GIS in order to effectively preserve buildings with cultural values.

As shown, the total number of scholarly materials identified prior to 2014 is minimal with only thirteen articles published. Starting from 2014 onwards, the application of CIM has



Note(s): That the low number of publications identified in 2022 is because the search was done on early 2022; thus, an upwards trend is expected for 2022

Figure 2.
Illustration of trends in publication per year

gained momentum evidenced by 182 articles published between 2014 and 2022, an average of almost 20 articles published annually. This average is higher than the total number of publications existing before 2014. A steady increase can be seen in the trend of publication from 2019 and the following years. The highest number of publications is recorded with 50 articles published in 2021, a 285% increase compared to the period between 2001 and 2013. This indicates an ever-increasing interest in the application of CIM. Considering the current trend of publication, it is expected that the interest in the topic would continue to grow in the future.

Figure 3 illustrates the extent of international interest in the application of CIM, including 42 countries that are stretched over six continents (Figure 3). With 37 articles, China is the country with the highest number of publications in the field which represents 19% of the total articles published globally since 2001 (See Table 2). Australia (19) is the second country with a high number of publications, followed by the USA (18), the UK (16) and Germany (11). In a continental context, however, Europe contributed the highest number of publications in the field (e.g. 80 articles) with the UK, Germany, Italy and Sweden being the most active countries. This is followed by Asia (67), North America (21), Oceania (19), South America (4) and Africa (4).

The findings of this section suggest an exponential increase of interest in the use of CIM within a global context over recent years. This signifies the necessity of developing a comprehensive understanding of CIM implementations in urban environments. The following sections aim to discuss the current trend of CIM implementations in the built environment, along with providing a view of current challenges facing the widespread adoption of CIM.

3.2 The current implementations of CIM

The contents of selected studies have been qualitatively analysed to identify the prevalent areas of research related to CIM implementations. As a result, nine domains were singled out and the employment of CIM in these areas was critically discussed.

3.2.1 Natural disaster management. The effects of climate change triggered by the increase of anthropogenic activities have manifested over the recent decades as natural disasters, causing severe damages to settlements and economic losses. This has led to a paradigm shift in

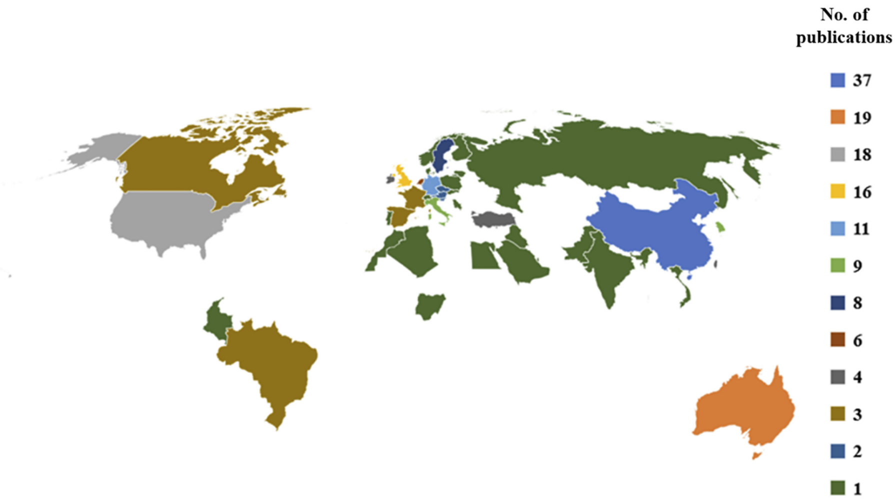


Figure 3.
Geographical distribution of identified studies

Countries	No. of publications identified per country
China	37
Australia	19
USA	18
UK	16
Germany	11
South Korea; Italy	9
Hong Kong; Sweden	8
Netherlands	6
Ireland; Turkey; Taiwan	4
Singapore; Brazil; Spain; France; Canada	3
Slovenia; Austria; Czech Republic	2
Colombia; Algeria; Poland; Nigeria; Russia; Serbia; Morocco; Pakistan; Egypt; Norway; Iraq; Qatar; Saudi Arabia; Denmark; Portugal; Finland; Switzerland; India; Slovak Republic; Vietnam; Lithuania	1

Table 2.
Origins of identified studies

urban design by moving from "disaster vulnerability" to "disaster resilience" in order to develop resilient communities (Sajjad *et al.*, 2021). In this regard, the CIM can play an important role in enhancing the predictability of occurring natural disasters and developing viable strategies to increase urban resilience (Park and Seo, 2021; Lu *et al.*, 2020b; Lei *et al.*, 2020; Isikdag *et al.*, 2007). The review showed that studies implemented CIM for various purposes including analysis and mitigation of risks associated with earthquakes (Park and Seo, 2021; Trendafiloski *et al.*, 2009; Lu *et al.*, 2019), fire response management (Ma *et al.*, 2019; Isikdag *et al.*, 2007) and urban flood inundation (Rong *et al.*, 2020; Singh and Garg, 2016). For instance, Rong *et al.* (2020) developed hydrodynamic models to quantify the risks associated with floods in a coastal city. To this end, the BIM and GIS were used to generate a digital city model using digital aerial photogrammetry for the 3D hydrodynamic model. The results suggested that the use of 2D hydrodynamic assumptions and approximations may compromise the flood prediction accuracy if vertical fluctuations would be massive, especially in urban environments. Comparatively, the use of a 3D model powered by high-resolution topographic data can procure precise estimations for the complex flow field. It was conclusively stated that the application of a 3D hydrodynamic model combined with the digital city model can significantly enhance the possibility of flood prediction and prevention in urban environments.

This review also found studies that aimed to devise CIM-powered frameworks with the capacity of predicting hazards in areas subject to multiple disasters (Lu *et al.*, 2020b; Lei *et al.*, 2020). For instance, Lei *et al.* (2020) proposed the development of a cyber-physical based intelligent framework that enables prevention of natural disasters within urban contexts using sophisticated technologies coupled with BIM platforms. The basis of the framework was on employing four core technologies including hardware (e.g. sensing and automation hardware), software (e.g. industrial software), network (e.g. industrial network and cloud systems) and platform (e.g. intelligent service platform). These technologies were thence consolidated into three major subsystems/layers, namely "perception layer", "communication layer" and "information layer". The perception layer is where the physical world becomes digitalised using various intelligent sensing technologies such as "video image", "multi-monitoring", "multi-scale collinear monitoring" and "corrosion monitoring". The second layer facilitates cross-platform interconnection and convergence between heterogeneous networks and systems using technologies such as the internet, wired networks, wireless sensor networks, or general packet radio service. The improvisation of this layer assures that CIM platforms are always powered with real-time data. The information layer recognises risks being imposed on urban structures by earthquakes, wind disasters and corrosion via intelligent algorithms such as distributed computing, parallel computing, utility computing, network storage, virtualization, load balancing and big data analysis processing. These layers were then integrated with BIM platforms to support project information sharing.

CIM is a useful tool for optimising the management of natural disasters in urban areas. This review found that the implementation of CIM can assist decision-makers to develop prevention strategies in dealing with natural disasters such as floods, cyclones, or bushfires. CIM offers the possibility to identify areas susceptible to natural disasters, then develop and prioritise viable strategies to mitigate the effects of such disasters by running comprehensive multi-hazard simulations.

3.2.2 Urban building energy modelling. Urban building energy modelling (UBEM) is a simulation approach towards evaluating the performance of a cluster of buildings within an urban context, providing the possibility to capture the dynamics of individual buildings, inter-building effects and urban microclimates (Hong *et al.*, 2020; Ang *et al.*, 2020; Omrany *et al.*, 2022b). UBEM is a fast-growing, interdisciplinary research area where computer science is coupled with urban sensing, data management and data analytics to assess city-scale energy and environmental systems (Hong *et al.*, 2020). The areas of UBEM research identified by this review include archetype identification (Deng *et al.*, 2022; Mauree *et al.*, 2017; Dogan and Reinhart, 2017), urban building database development (Deng *et al.*, 2021b; Chen *et al.*, 2019; Monteiro *et al.*, 2018), validation and calibration of urban modellings (Kristensen *et al.*, 2018; Mohammadiziazi *et al.*, 2021) and enhancing operational efficiency of building stock (Chen *et al.*, 2017; Wang *et al.*, 2021; Omrany *et al.*, 2021).

The full implementation of UBEM requires the attainment of comprehensive building-related information (e.g. building geometry, highest age, functionality, total floor area or heated floor area) and non-geometric parameters. In general, there are two main approaches towards implementing UBEM, namely the top-down and bottom-up (Deng *et al.*, 2022; Chen *et al.*, 2019). The first approach analyses energy consumption of urban buildings in an aggregated way, considering the impacts of various socioeconomic factors. In this approach, data-driven from statistical and regression models integrated with building stock data, technology and economical models are used to supply a comprehensive building energy policy evaluation and scenario analysis, as well as a technology R&D roadmap (Hong *et al.*, 2020). Contrarily, the bottom-up approach considers the evaluation of energy usage associated with individual buildings in a disaggregated way. In the bottom-up approach, buildings and urban systems are modelled using fully detailed dynamic building physics modelling techniques, reduced-order dynamic models, or data-driven models by adopting machine learning techniques (Hong *et al.*, 2020). Apart from building information, many non-geometric parameters should also be considered when developing UBEMs such as internal loads, heating and cooling systems and ventilation (Deng *et al.*, 2022; Chen *et al.*, 2019). Therefore, the development of archetypes becomes essential in order to facilitate the process of data collection.

Building archetypes generally represent the most ubiquitous typologies and properties in building stocks. In this regard, studies proposed methods for identifying archetype buildings aiming to generate UBEMs when detailed information is unavailable. In recent research, Deng *et al.* (2022) selected a sample of 68,966 buildings in Changsha city, China for archetype identification. To this end, the type of each building footprint based on different GIS datasets was determined using clustering and random forest methods. Thereafter, the year built of commercial and residential buildings were determined using a convolutional neural network based on historical satellite images from several years and the housing website, respectively. Further, 22 building types and three vintages were selected as archetypes to represent 59,332 buildings, covering 87.4% of the total floor area. The building energy models for the archetype buildings were also produced using Ruby scripts leveraged on OpenStudio-Standards. Finally, the energy performance of urban building archetypes including monthly and annual electricity and natural gas energy was simulated using EnergyPlus. The development of such models could be beneficial for assessing the impacts of different conservation strategies on saving energy for an entire city.

The development of a city-scale dataset encompassing the current building stock is a vital measure in enabling UBEMs to automatically generate and simulate urban building energy models. The data needed for UBEMs typically include GIS footprint, building height, number of stories above and below the ground, total floor area, heated floor area, number of dwellings, year of construction and/or refurbishment, building functionality, heating system type, annual electricity and natural gas usage (Chen *et al.*, 2019). In a study, Deng *et al.* (2021b) proposed a comprehensive framework for database development of a city in China by integrating GIS based point-of-interest (POI) and community boundary datasets. The selected case study included a total of 68,966 building footprints, 281,767 POI data (e.g. entity name, entity category and entity sub-category) and 3,367 community boundaries. A validation was performed for a collection of 7,895 buildings in the downtown area, which demonstrated an overall accuracy rate of 86%.

Another challenge concerned with developing a city-scale database attributes to collecting and assigning enough detailed data inputs for the establishment of a fully-functioning UBEM without making many assumptions and simplifications. Hence, studies developed methods for calibration and validation of archetypes for urban building energy modelling (Kristensen *et al.*, 2018; Mohammadiziazi *et al.*, 2021). Kristensen *et al.* (2018) assessed the applicability of two bottom-up approaches, namely physical modelling and a data-driven approach for modelling urban neighbourhoods. The first method was represented by a GIS-based automated modelling approach, including a detailed dynamic building simulation in IDA ICE whereas the data-driven method utilised a non-linear data-driven method for obtaining the required data. The results indicated the applicability of both methods for aggregating urban building data by showing a sufficient agreement between simulated and measured data. Indeed, this review found studies that employed UBEMs as a tool to support decision-making for improving the energy efficiency of building stocks (Buckley *et al.*, 2021; Chen *et al.*, 2017; Wang *et al.*, 2021). For instance, Buckley *et al.* (2021) developed a UBEM to evaluate the effectiveness of energy retrofitting policies for neighbourhoods in Ireland by quantifying the most cost-effective alternatives for revamping buildings' envelopes and onsite energy productions.

The review showed that UBEM is an effective decision-making tool that can be employed by different stakeholders to comprehensively evaluate the effects of various energy efficiency and energy production scenarios on an entire city, neighbourhood, or district. Nevertheless, UBEM faces a number of challenges that should be addressed by future research to unleash the full potential of this concept. The standardisation of data input formats for sharing urban building assets, increasing the accuracy of urban building archetypes to better represent building stocks and enhancing computing resources to carry out exascale calculations related to the energy use of the entire building stock within a reasonable time, are a number of these challenges.

3.2.3 Urban facility management. In recent years, there has been an increasing interest in real-time management of urban facilities by incorporating information and communication technologies (ICTs) into physical infrastructures, collecting comprehensive spatial and status data of various urban facilities in order to improve urban facility management (UFM) (Lee *et al.*, 2013). Aligned with such an increase in interest, the application of CIM has also been on the rise, facilitating the transition of UFM from conventional management practices that are often relied on manual maintenance to more intelligent ones. This review identified three main domains of research that implemented CIM for the purposes of UFM, namely the practise of intelligent UFM (Qian and Leng, 2021; Ma *et al.*, 2021; Mignard and Nicolle, 2014), the reconstruction of post-conflict cities (Assem *et al.*, 2020) and preservation of historical/heritage cities (Youn *et al.*, 2021; Tschirschwitz *et al.*, 2019; Fadli and Alsaeed, 2019).

Mignard and Nicolle (2014) presented a new approach for intelligent UFM by developing semantic extensions to the BIM consisting of spatial, temporal and multi-representation concepts. To this end, an evolutionary BIM-related ontology was developed to enable the retrieval of information pertaining to urban facilities such as buildings, their surrounding environments, urban elements and their associated networks. The retrieved information can then be merged with data received from GIS to optimise the 3D representation of urban facilities. The employment of this framework by facility managers can support their decision-making within a collaborative context. In another study, Assem *et al.* (2020) devised a framework for the reconstruction of cities subjected to wars, e.g. Damascus, Sarajevo, Baghdad and Aleppo using CIM. In this sense, BIM, GIS and web-based technology were integrated towards the development of a platform that would enable users to effectively manage reconstruction operations by performing real-time analyses, reporting, strategic planning and decision-making, as well as facilitating collaborations between stakeholders.

The CIM has also been proven as an instrumental tool when applied to heritage/historical cities. For instance, Tschirschwitz *et al.* (2019) created a digitalised version of the historical city of Duisburg, Germany for knowledge deepening purposes and enhancement of visitors' experience in exploring heritage cities. The digitalisation was carried out using data obtained from laser scanning techniques coupled with employing virtual reality technologies. Studies also used the CIM approach for preservation purposes of heritage urban contexts and building restoration (Youn *et al.*, 2021; Fadli and Alsaeed, 2019). This can be seen in the research done by Fadli and Alsaeed (2019) that investigated possibilities for constructing Qatar's historic buildings information modelling platform. To realise this aim, extensive site analyses were carried out using topographic recording, photogrammetric and 3D scanning techniques, combined with performing in-depth interviews. The findings introduced principles for developing an interactive digitized tool that would enable the representation of massive data about heritage buildings through an expandable database using advanced BIM technologies.

The findings of this review suggest that the implementation of CIM for UFM purposes may offer unique opportunities for active and intelligent monitoring of urban facilities and the reduction of financial and human losses caused by failure of these structures, effective management of operations carried out for rebuilding cities subjected to massive deconstruction and possibilities for preserving historical cities.

3.2.4 Urban infrastructure management. The urban infrastructures are critical components, both below and above the ground due to their critical roles in maintaining cities' functionality. To date, the common approach in urban infrastructure management involves treating urban infrastructural utilities individually using conventional methods (e.g. periodic manual maintenance checks) (Ma *et al.*, 2020). Nevertheless, the management of urban infrastructural systems through the conventional methods is becoming increasingly difficult due to the sprawl of cities, highlighting the necessity of transitioning from a short-term *ad hoc* maintenance to a comprehensive integrated repair approach that can effectively increase urban resilience and sustainability. In this regard, CIM can constructively contribute to facilitating such a transition. This review identified a number of areas in which CIM was implemented for purposes of urban infrastructure management including utility management (Zhao *et al.*, 2019b; Wang *et al.*, 2019), transportation (Zhao *et al.*, 2019a; Park *et al.*, 2019; Deng *et al.*, 2016), bridge maintenance (Zhu *et al.*, 2021; Shim *et al.*, 2019), smart wastewater management (Edmondson *et al.*, 2018; Howell *et al.*, 2017) and risk assessment of ground settlement caused by tunnelling in urban areas (Providakis *et al.*, 2019; Lee *et al.*, 2018; Le and Hsiung, 2014).

The research carried out by Wang *et al.* (2019) aimed at improving the efficiency of underground utility management by proposing a framework based on the integration of BIM and GIS. The framework consisted of a utility data model representing utility information in five areas, e.g. utility network, utility component, utility geometry, utility condition and utility miscellaneous. The verification results showed that the data collected via the utility data model and transmitted to the integrated BIM-GIS platform led to developing functions that could effectively support underground utility management in terms of both individual utility components and the utility spatial networks.

CIM has also been implemented in the area of transportation for purposes such as optimization of highway alignment (Zhao *et al.*, 2019a), developing a framework for mapping 3D traffic noise by utilizing data obtained from BIM and GIS (Deng *et al.*, 2016) and route optimization of snow-removal vehicles using CityGML-Based Road Information Model (Park *et al.*, 2019). For instance, Zhao *et al.* (2019a) proposed a framework for managing highway alignment in urban areas using an integrated BIM and GIS approach supported by semantic web technologies. The semantic translation of data received from BIM and GIS was done using Resource Description Framework which is a technique enabling computers to read and interpret semantic information across the Internet (Zhao *et al.*, 2019a). The proposed framework also included genetic algorithms to help with optimisation of the highway alignments. The applied model indicated promising results for optimal determination of highway alignment, offering the possibility to minimise design errors and miscommunication as a result of providing visualization of the highway project and its surroundings, identifying geohazards and environmentally sensitive regions by performing geological and geographical analyses.

The findings of studies also reported improvements in the process of design, construction and maintenance of urban infrastructures achieved due to adopting CIM. This is echoed in the research carried out by Zhu *et al.* (2021) that developed a Web GIS-based bridge management system to facilitate data exchange between industry foundation classes (IFC) files and GIS. The validation yielded promising results for the improvement of bridge maintenance management. Howell *et al.* (2017) also aimed to enhance the delivery of value-added services to consumers and network operators by devising a semantic knowledge management service and domain ontology capable of supporting novel cloud-edge solutions through unifying domestic socio-technical water systems with clean and waste networks at urban scales. The findings suggested that massive data obtained via merging semantic web technologies with IoT can lead to developing solutions for smart management of water supply in cities. In another study, Lee *et al.* (2018) proposed an integrated system framework to improve the maintenance performance of utility tunnels in urban areas. The developed framework consisted of BIM and 3D-GIS with required maintenance management functions incorporated into the framework. The results pointed out the effectiveness of the proposed framework for delivering maintenance works in tunnels.

3.2.5 Land administration systems. The rapid urbanisation, in tandem with population growth, has led to establishment of high-rise buildings as an effort to accommodate the increasing demands for housing. This has subsequently created functional and physical complexities in cities with dense spatial environments, posing certain challenges to the conventional land administration systems for handling legal boundaries and rights, restrictions and responsibilities related to private, communal and public properties, as well as land valuation and taxation assessment, planning and controlling land use and natural resources (Barzegar *et al.*, 2021a, b; Atazadeh *et al.*, 2021).

To address these challenges, there has been a growing interest in developing 3D land administration systems and employing 3D data to facilitate the registration process, improve transparency in land and property transactions, save time and cost and enhance land use management (Barzegar *et al.*, 2021a). For instance, Atazadeh *et al.* (2021) developed a 3D digital cadastre by incorporating 3D information extracted from an open BIM-based data model, also known as IFC into the Land Administration Domain Model (LADM) with the least possible disruption in the structure of IFC. The results underlined the possibility for the visual representation of cadastre by creating a linkage between BIM and LADM environments. This may further lead to minimising issues related to legally delineating boundaries of lands in cities. Sun *et al.* (2019) also proposed a framework to integrate data of LADM models with BIM and GIS on building and city levels aiming to increase the accuracy of representing legal boundaries and visualising 3D cadastre in urban environments. The results suggested that the integration of cadastral information with BIM/GIS is feasible, indicating possibilities for better representation of 3D cadastral boundaries in urban areas.

Another stream of research targets at adding legal and ownership dimensions to the digitalisation of land administration systems in urban areas. This idea represents a research gap in which the current urban data models such as IFC and CityGML are largely focused on the physical and functional attributes of urban properties while ignoring their corresponding legal and ownership aspects. Hence, the addition of such aspects may enhance the effectiveness of land administration practices. For instance, Aien *et al.* (2015) proposed a data model that supports the integration of legal and physical information related to urban environments. The outcomes provided a proper basis for applications that require an integrated resource of both legal and physical information such as urban space management and land development processes. Ying *et al.* (2021) proposed a model for the easement of access, which is the right to enter a property from another parcel of land, under the context of 3D cadastres that facilitates the incorporation of semantic data including spatial information of 3D properties retrieved from IFC-BIM models into legal information. The results indicated the integration of legal information with 3D spatial information associated with urban properties and facilities may help with improving land management and accelerating the development of 3D cities.

CIM has also been implemented for the purpose of property valuation, facilitating the integration and exchange of data attributed to legal, physical, environmental, geometric and location characteristics of lands, coupled with economic factors that are needed for effective value evaluation of properties (El Yamani *et al.*, 2021; Kara *et al.*, 2020). For instance, El Yamani *et al.* (2021) proposed a data model for the value assessment of properties with reliance on information acquired from BIM and CIM models. The model was capable of using data pertained to spatial and non-spatial variables via BIM (e.g. buildings' height, geometry) and CIM (e.g. vegetation, transportation, land use, noise level, air quality, quality of view, sunlight exposure) models and account for their respective impacts towards appraisal of properties' values.

3.2.6 Improvement of urban microclimates. Citizens in urban environments are being increasingly exposed to adverse effects caused by urbanisation such as global warming and the urban heat island. This highlights the necessity of making cities climate-proof by considering designing measures that can optimise micrometeorological variables (e.g. air temperature, humidity, solar radiation and wind speed and direction), hence improving urban microclimates (Jänicke *et al.*, 2021). A number of variables can contribute to the optimisation of outdoor microclimates of cities such as urban morphology, green spaces and vegetation, water bodies, surface of urban materials and ventilation (Jänicke *et al.*, 2021). Studies showed that the use of CIM can be beneficial in designing climate-sensitive cities by comprehensively accounting for the effects of such factors (Dantas *et al.*, 2019; Fernández-Alvarado *et al.*, 2022). In this regard, Dantas *et al.* (2019) demonstrated the capacity of CIM for evaluating the quality of citizens' lives in cities. They employed CIM to retrieve data from urban environments corresponding to indicators of ISO 37120 (Sustainable Development of Communities – Indicators for City Services and Quality of Life) (ISO 37120, 2018). The results showed that the application of CIM can provide accurate data for 53 out of 100 existing indicators. Such an application of CIM can assist urban policymakers and city managers in comprehensively evaluating the effects of their decisions on the quality of people's lives.

Fernández-Alvarado *et al.* (2022) also endeavoured to measure the potential risk of citizens' exposure to urban green infrastructure by calculating an aerobiological index, namely the Aerobiological Index of Risk for Ornamental Trees (AIROT). The AIROT is an index used to measure risks of pollen exposure associated with urban green infrastructures imposed on individuals. To realize the objective, a 3D model of the urban area was constructed using a high level of detail (LOD) buildings' data captured via LiDAR. The outcomes provided insights for decision-makers about urban green infrastructure management such as considerations for replanting, pruning, or removing trees tasks so that the risk of exposure could be minimized.

The literature suggests that the adoption of CIM offers superb opportunities for improving urban microclimates. CIM provides a platform for target communities to holistically understand the effects of their decisions on urban microclimates during different stages of urban development. The use of CIM also facilitates the compliance of urban designs with international standards by providing accurate data related to urban buildings and operating systems of cities. This may further lead to promoting best practices for urban development within a comparable global context.

3.2.7 From smart cities to digit twin of cities: the key role of CIM. Over the last two decades, the advancement of ICTs has facilitated the transition of cities towards becoming smarter by providing real-time data collected from multiple sources in cities such as power production, urban infrastructures, or water supplies (Ramu *et al.*, 2022; White *et al.*, 2021; Shahat *et al.*, 2021). The availability of such data, in corollary, can help with monitoring activities in urban environments and assist with improving mobility, environments, quality of life and governance of cities (White *et al.*, 2021; Deng *et al.*, 2021a). The increased availability of data acquired from smart cities has further triggered the emergence of digital twins. The concept of digital twin resides with developing a virtual replica of a city and pairing it with the physical version so that the digitalised twin becomes updated once changes occurred in the physical equivalent (Ramu *et al.*, 2022; Shahat *et al.*, 2021; Deng *et al.*, 2021a). Development of such models enables conducting comprehensive data analysis and monitoring of urban systems to identify potential failures prior to their occurrence, preclude downtime and can also be employed for future development of cities using parametric simulations (White *et al.*, 2021). Digital twins also allow for juxtaposing various scenarios and prioritising them in accordance with their weighted strengths and weaknesses for tackling certain issues (White *et al.*, 2021; Ramu *et al.*, 2022; Shahat *et al.*, 2021). This capacity is beneficial in urban planning, allowing decision-makers to comprehensively understand the consequences of their decisions. Virtual Singapore is an exemplar of a city's digital twin, a collaborative data platform that provides a dynamic 3D model of the city (Virtual Singapore, 2021). Other examples of cities' digital twins that are under development include Zurich (Schrotter and Hürzeler, 2020), Adelaide (Aerometrex, 2022), Helsinki (Cousins, 2017) and New York City (Cities Today, 2021).

Fundamental to the development of a city's digital twin is the sub-models constructed at different scales to represent various entities in the urban context such as buildings, urban systems and infrastructures, or assets (Ramu *et al.*, 2022; Shahat *et al.*, 2021). CIM is an integral component of digital twins used to describe information modelling at the city level. Sub-models built using CIM and BIM techniques are powered with real-time data collected via intelligent functions (e.g. remote sensors, IoT, or AI) from urban objects and transmitted to the models. Hence, the functionality of a digital twin rests on integrating sub-models and establishing secure paths for flowing data from urban objects to sub-models, as well as exchanging data between models.

This review found that CIM has been a prevalent tool implemented for developing digital twins in urban contexts for purposes such as collaborative urban design (Pang *et al.*, 2021; White *et al.*, 2021), urban road planning (Jiang *et al.*, 2022), urban disaster management (Fan *et al.*, 2020, 2021; Ham and Kim, 2020; Ford and Wolf, 2020), urban energy management (Francisco *et al.*, 2020), evaluation of CO_2 emissions in cities (Park and Yang, 2020) and monitoring of citizens' comfort (Zaballos *et al.*, 2020). For instance, Lu *et al.* (2020a) developed a digital twin of the West Cambridge site of the University of Cambridge in the UK. In this research, CIM played a critical role in modelling information at the city level. The architecture of the twined model consisted of five layers including data acquisition layer, transmission layer, digital modelling layer, data/model integration layer and service layer. In the layer of digital modelling, a three-sublayer digital model was constructed based on different levels of information. This included modelling geometry of the West Cambridge site at a city level, modelling buildings with a medium LOD, e.g. including architecture, structure and mechanical and electrical and pumping components using BIM techniques and a BIM model of specific areas in the buildings with highly detailed information (e.g. facilities and pipes in the plant room) at a building level. The data relating to the site was acquired via fixed-wings drones and vehicle-based scanning devices. Further, laser scanners and digital cameras were utilised to capture highly detailed 3D geometry scans of the buildings' interiors.

Despite the increasing interest, there is still room for improvement of CIM applications in developing digital twins of cities. Studies pointed out the lack of accuracy in modelling information at the city level when dealing with high LOD modellings (Shahat *et al.*, 2021). Capturing non-physical components such as the cultural background of a region/city and incorporating their effects into CIM models is also a challenging task. This issue is compounded in cases where participatory sensing and crowdsourced data are utilised to supplement limitations concerned with sensory information in digital twin models as localization errors and untrusted data may occur (Shahat *et al.*, 2021). This further can compromise the quality of simulation results, thus affecting the decision-making process.

3.2.8 Improvement of social engagement. CIM can be employed for the enhancement of cities' liveability by identifying opportunities to improve social wellbeing of individuals. The findings of this review indicated scant attention given to the implementation of CIM towards such an end. Amongst few are studies that adopted CIM for planning age-friendly cities (Zhang *et al.*, 2021; Ruza *et al.*, 2015; Jelokhani-Niaraki *et al.*, 2019). For instance, Ruza *et al.* (2015) developed a framework to assist with the systematic evaluation of the age-friendliness of cities using web-based GIS tools. The proposed framework was then applied to the city of Palo Alto, California as a case study. The results identified possibilities such as providing open spaces, public transportation and services for the aged population through which the city can become more age-friendly. In a recent study, Jelokhani-Niaraki *et al.* (2019) devised a tool based on integrating Volunteered Geographic Information, GIS and multicriteria decision analysis techniques in order to quantitatively assess the age-friendliness of urban areas. The device facilitated assessing the age-friendliness of urban areas via integrating weights of certain criteria with volunteered geographic information obtained by citizens. The tool's applicability was tested in the city of Tehran, Iran and the results were indicative of the tool's capacity for evaluating the city's age-friendliness.

The findings of this review showed that the use of CIM offers great opportunities for elevating the age-friendliness of cities and assures retaining the quality of life as citizens age. This can be done by using CIM to assess the age-friendliness of urban environments (e.g. performing comprehensive evaluations of municipal services provided for the elderly), identify possibilities for improvements (e.g. accessibility of urban services) and evaluate the viability of various strategies to ameliorate the situation.

3.2.9 Urban landscaping design. The adoption of CIM has evolved the discourse of urban design by providing a platform for better collaborations (Alashi and Koramaz, 2019; Cousins, 2017); supporting decision-making in urban landscaping design (Urech *et al.*, 2022; Kong *et al.*, 2022); analysing future design scenarios based on real-time data (Urech *et al.*, 2020) and facilitating the design of safe, cost-effective and ecologically friendly environments (Yeo and Yee, 2016; Kim *et al.*, 2016; Stojanovski *et al.*, 2020). For instance, CIM facilitates the dynamic design of urban environments. The use of digital tools and 3D models for urban designing has been around for decades; however, the majority of the objects such as buildings, vegetation, open spaces, streets, urban topographies, or water features presented in conventional 3D models are static, hence limiting applications for dynamic analytical purposes. Urech *et al.* (2022) attempted to address this limitation by proposing a framework that enables developing multiple design scenarios and dynamically evaluating the effectiveness of developed scenarios on urban landscapes. The framework first establishes a thorough geometric documentation of urban areas using laser-scanned point cloud modelling techniques and then converts the geometric data from point cloud models into voxels and meshes to allow for further dynamic analyses. The implementation of this framework can support target communities such as city managers, urban designers and landscapers to make informed decisions based on real-time feedback.

The findings of recent research also attest to the contribution of CIM for increasing the accuracy of measuring outdoor thermal environments (Kong *et al.*, 2022; Chen *et al.*, 2014). In general, the shading pattern and radiation fluxes are influenced by the complex 3D configurations of urban landscapes which further affects thermal comfort of outdoor environments. The use of CIM with the reliance on acquiring precise data on the status-quo of urban geometries allows for capturing a holistic understanding of urban landscape configurations. This is reflected in the research carried out by Kong *et al.* (2022) that measured the impacts of 3D urban landscape patterns on the outdoor thermal environment at an urban scale by fusing the 3D landscape metrics calculated from LiDAR point-clouds and the UMEP tool. The results indicated promising achievements in enhancing outdoor thermal comfort of urban environments due to considering the full impacts of 3D urban landscape patterns. The development of such models can help with formulating planning and design strategies to promote thermally comfortable urban environments.

CIM has also been implemented as an instrumental tool to support developing designs compatible with urban ecology (Xian and Zhang, 2021; Yeo and Yee, 2016) and designing safe environments for citizens' activities, e.g. walking or cycling (Campisi *et al.*, 2020; Kim *et al.*, 2016). Yeo and Yee (2016) developed an automated module of a knowledge-based urban planning system that can support the implementation of environmentally-friendly planning schemes. The module was capable of integrating planning data received in different formats and synthesizing them into a unified format during the planning stage. The architecture of the module system accounted for the formation of building polygons, textures for classified land cover shape, topography and 3D urban space. The implementation results suggested that the use of modules can support eco-friendly city planning. In another study, Kim *et al.* (2016) developed an ontology-based framework using BIM and GIS to support *Safe Routes To School* programs in the US. The use of this framework enables a consistent supply of information about the existing urban walking infrastructures with connections to schools and reports on areas that require improvements. The development of this framework promoted walking/biking behaviours amongst students, hence improving the health of students as well as reducing energy consumption.

4. Challenges of CIM uptake

This study has comprehensively investigated the current implementation of CIM in the built environment. The findings showed that there has been an increasing interest in employing CIM over the recent years. Table 3 tabulates nine areas of implementation, along with potential benefits, reported to have been achieved by the analysed studies due to using CIM. As shown, the adoption of CIM can offer unique opportunities contributing to the improvement of decision-making in urban planning and urban design. Nevertheless, the uptake of CIM still faces a number of challenges that should be addressed by future research. This section summaries a number of these challenges.

(1) *Reluctance towards CIM application.* Despite the potential of CIM, stakeholders are still reluctant to employ this tool for urban planning and management purposes. This hesitancy could be due to multiple reasons such as the lack of knowledge about

Identified domains of CIM implementation	Sub-domains of CIM implementation	Benefits reported by the reviewed studies
Natural disaster management	• Analysis and mitigation of risks associated with earthquakes • Fire response management • Analysis urban flood inundation	• Identifying urban areas susceptible to natural disasters • Predicting the occurrence of hazards in areas subject to multiple disasters • Developing prevention strategies to deal with natural disasters and testing their corresponding effectiveness in mitigating natural disasters' effects • Increasing urban resilience
Urban building energy modelling	• Archetype identification • Urban building database development • Validation and calibration of urban modellings • Enhancing operational efficiency of building stock	• Providing the possibility of assessing the impacts of different conservation strategies on saving energy for an entire city • Developing city-scale dataset so that UBEM can automatically generate and simulate urban building energy models • Analysing the effectiveness of energy retrofitting policies on a neighbourhood scale
Urban facility management	• The use of intelligent UFM. • The reconstruction of post-conflict cities • Preservation of historical/heritage cities	• Active and intelligent monitoring of urban facilities and the reduction of financial and human losses caused by failure of these structures • Increasing collaboration between facility managers • Supporting decision-making • Preservation and restoration of heritage urban contexts and buildings
Urban infrastructure management	• Utility management • Urban transportation management • Bridge maintenance • Smart wastewater management • Risk assessment of ground settlement caused by tunnelling in urban areas	• Improving the efficiency of underground utility management • Optimizing highway alignment • Mapping 3D traffic noise • Route optimization of snow-removal vehicles • Improving infrastructures' maintenance

(*continued*)

Table 3. An overview of CIM implementations and benefits

Table 3.

Identified domains of CIM implementation	Sub-domains of CIM implementation	Benefits reported by the reviewed studies
Land administration systems	• Using CIM to facilitate the registration process, increasing transparency in land and property transactions • Adding legal and ownership dimensions to the digitalisation of land administration systems in urban areas • Property valuation assessment	• Improving land use management, saving time and cost associated with land administration and registration processes • Reducing issues related to legally delineating boundaries of lands in cities • Comprehensive value assessment of properties • Useful for applications where legal and physical information should be integrated, e.g. urban space management and land development processes
Improvement of urban microclimates	• Microclimate design • Evaluating the quality of citizens' lives in cities • Assessing risks of citizens' exposure to dangerous particles in urban areas	• Designing climate-sensitive cities by comprehensively accounting for the effects of micrometeorological variables • Enabling urban policymakers and city managers to comprehensively evaluate the effects of their decisions on the quality of people's lives • Providing insights for decision-makers about urban green infrastructure management (e.g. replanting, pruning, or removing trees) • Compliance of urban designs with international standards
Development of digital twin and smart cities	• Developing digital twins for purposes such as collaborative urban design; urban road planning; urban disaster management; urban energy management; evaluation of CO_2 emissions in cities and monitoring of citizens' comfort	• CIM is an integral component of digital twins used to describe information modelling at the city level
Improvement of social engagement	• Improving cities' liveability • Planning age-friendly cities	• CIM can support the design of age-friendly cities by providing possibilities for improving open spaces, public transportation and services for the aged population
Urban landscaping design	• Dynamic design of urban environments • Increasing the accuracy of measuring outdoor thermal environments • CIM supports developing designs compatible with urban ecology and designing safe environments for citizens' activities, e.g. walking or cycling	• Improving collaborations; supporting decision-making in urban landscaping design; analysing future design scenarios based on real-time data; facilitating the design of safe, cost-effective and ecologically friendly environments; dynamizing the design of urban environments; designing and planning thermally comfortable urban environments

the potential of CIM among leadership, lack of trust in results obtained via CIM, not including the necessity of using CIM in contracts, lack of investment in promoting the use of CIM, lack of training, lack of synergy between collaborators for using CIM and/or the absence of knowledge for utilising CIM (Pereira *et al.*, 2021).

(2) *Data quality*. Developing 3D models of cities requires acquiring immense amounts of geometrical, spatial and semantic data about urban environments. Masson *et al.* (2020) grouped the input data needed for urban modelling into five categories including land cover, building morphology, building design and architecture, building use, anthropogenic heat and socio-economic data and urban vegetation data. A plethora of methodologies can be used for obtaining the required data such as remote sensing, crowdsourcing, expert knowledge, or GIS data processed from administrative cadastres. Hence, retaining the quality and integrity of data can be challenging, given the diversity of existing methodologies and resources for urban data retrieval.

(3) *Computing resources and storage inefficiency*. Performing comprehensive simulation analyses of a city' performance which may involve millions of components (e.g. buildings, or infrastructures) requires exascale computing capacities that can only be realised through the next-generation supercomputers (Hong *et al.*, 2020). The management of data storage has also become a challenge in CIM application, especially with the emergence of big data in urban modelling that involves collecting, processing, analysing and interacting with heterogeneous data (Lv *et al.*, 2020; Li *et al.*, 2020). This may call for developing new data management architecture with the capacity to accommodate geospatial characteristics of data, e.g. multi-sourced heterogeneity and dynamic nature of data.

(4) *BIM and GIS; data integration and interoperability*. Interoperability facilitated via open standards such as CityGML is essential for the effective reuse and exchange of data, as well as enabling reciprocal integration of different data formats (Groger and Plumer, 2012). CityGML is the international standard of the Open Geospatial Consortium developed in 2008 to assist with exchanging data in 3D city models (Groger and Plumer, 2012). Despite many attempts undertaken, studies have highlighted a number of issues related to the CityGML standard (Noardo *et al.*, 2021; Ledoux *et al.*, 2019). From a practical perspective, the GML encoding of CityGML files can be highly complex which makes it unfriendly for users (Ledoux *et al.*, 2019; Arroyo Ohori, 2020). Further, difficulties concerned with parsing CityGML files, interpreting all the various ways in which geometries could be stored, resolving XLinks, coping with different Coordinate Reference Systems and providing support for ADEs (i.e. application domain extensions) are other issues of CityGML standard (Ledoux *et al.*, 2019; Arroyo Ohori, 2020). Moreover, interoperability has been only studied on a technical basis, e.g. facilitating the exchange of data between GIS and BIM models. However, issues related to interoperability should be further studied in other dimensions such as semantic or legal. Addressing this issue would enable delivering the projects more effectively.

(5) *Standardised workflow*. Despite the standards and tools developed to streamline CIM implementation, there is still a need for initiating a seamless workflow to further elucidate the requirements needed for CIM application and to standardise data inputs and procedures for carrying out CIM in the built environment.

(6) *Synergy*. Many research groups are actively working towards the advancement of the CIM concept, with several tools, methods and databases being increasingly developed. These efforts may never lead to promoting the uptake of CIM in urban

planning and management if failed to establish collaborations between all parties involved such as policymakers, urban designers and planners, researchers and developers. Collaborations would help with increasing the comparability and validity of CIM results, promoting the adoption of CIM to support cities in achieving their goals of sustainability, resilience, liveability and efficiency.

(7) *Cybersecurity and intellectual property.* Intellectual property and cybersecurity are among the main challenges concerned with using CIM. The implementation of CIM requires collecting, collating and sharing data between different individuals. This in turn may trigger the risks of unauthorised access to data and copyright infringement. Intellectual property can be another challenge in regard to the implementation of CIM in the built environment, given that the collection, processing and analysis of data are often handled by different experts in a team. Hence, this may pose certain challenges to licensing CIM models, as well as the adoption and reproducibility of CIM results.

(8) *Data management.* Well-developed CIM models rely on massive amounts of data received in varied formats. Synchronising these data and standardising their formats for interoperability requires significant efforts. Hence, standards and guidelines should be developed to streamline the process of metadata representation.

5. Conclusions and recommendations for future direction

This study aimed to provide a comprehensive understanding of CIM implementations in the built environments. To this end, 195 scientific materials were analysed. The results led to identifying nine main areas in which CIM was implemented. These include (1) natural disaster management, (2) urban building energy modelling, (3) urban facility management, (4) urban infrastructure management, (5) land administration systems, (6) improvement of urban microclimates, (7) development of digital twin and smart cities, (8) improvement of social engagement and (9) urban landscaping design. The analysis showed that the CIM implementation constructively leads to improving decision-making in all the identified domains. Nevertheless, the widespread application of CIM is currently being hampered by a number of challenges including reluctance towards CIM application, data quality, computing resources and storage inefficiency, data integration between BIM and GIS and interoperability, establishing a standardised workflow for CIM implementation, synergy between all parties involved, cybersecurity and intellectual property and data management.

In order to tackle these challenges, considerations should be given to promulgate the implementation of CIM across multiple disciplines involved in urban management. The first step towards this end is to increase the awareness of CIM and the associated benefits of its adoption in practise. This can be done by launching campaigns and workshops to enhance the awareness of the target audience about CIM's potential. It is also important that the current pedagogy system aims at training CIM modellers who can provide support to decision-makers during different stages of projects' execution. This may also imply that there is a need for a new profession in urban management, namely CIM modeller. Further, this study suggests that the use of CIM should be incorporated into contracts of urban projects, obligating managers to utilise CIM as a means to support the decision-making processes as well as facilitating collaborations. This can be coupled with necessitating the engagement of CIM modellers in projects. Finally, incentives can be provided to encourage best practices in a given sector. Incentives in form of subsidies and rebates or loans can be granted to companies and firms that would actively utilise CIM to promote best practices in urban management.

In addition, untapping the full potential of CIM is closely linked to future developments in computer science where advancements in the next-generation of supercomputers can assist

CIM models with processing massive data related to different entities in a city. There is also a need for developing protocols, guidelines and frameworks to standardize the process of data collection, data processing and data communication in the context of CIM implementation. This will, in turn, lead to improving the quality and integrity of data as well as data sharing between different CIM operating platforms. Another possible direction for the future development of CIM may be attributed to the development of protocols to protect the intellectual property rights of data and models generated via CIM implementation. This can be done by developing contractual templates so that parties can reach an agreement about the copyright ownership of CIM models.

The applicability of CIM in each of the areas identified by this study should be thoroughly investigated by going beyond simple case studies, quantifying the clear benefits of adopting this approach. The use of CIM is still in its infancy. There are many areas such as lifecycle thinking that can be potentially amalgamated with the concept of CIM to make it a much stronger tool in urban practices.

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