BETTER URBAN MANAGEMENT: A SYSTEMATIC REVIEW OF MULTI-SCALE DIGITAL MODELLING

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Abstract

Digital modelling has significantly progressed. Many scholars have reviewed and summarized the research of digital modelling. However, the reviewer needs to consider the practical applications of digital modelling at different scales. Multi-scale digital modelling (MSDM) refers to digital models that contain different levels of geometric or semantic details. This paper presents a systematic literature review (SLR) of MSDM. Distributed energy generation is one of the most worthwhile research directions. In the future, distributed energy generation systems - energy storage systems - and buildings or urban infrastructure should be interconnected based on MSDM.

Introduction

Digital modelling of buildings and cities is becoming an important research topic. Digital models of buildings, usually referred to as Building Information Models (BIM) or 3D building models, are detailed, accurate, and visual representations of buildings. BIM can be utilized across all stages of a building's complete lifecycle, including design, construction, operation, and maintenance (Qiu et al., 2021). In the design phase, BIM facilitates a more profound understanding among all stakeholders of the building's details and overall design compared to traditional 2D drawing models, allowing for the early identification of potential design issues such as clashes in piping or structural elements (Huh et al., 2023); in the construction phase, BIM aids in visualizing construction progress and enhancing on-site safety management (Tu et al., 2021); in the operation and maintenance phase, the energy consumption (Kamel and Kazemian, 2023) and carbon emissions (Lu and Deng, 2023) generated during the use phase of a building can be estimated from the site data collected by BIM and devices like sensors. A key benefit of BIM and equivalent technologies is their object-oriented nature, which ensures that models accurately represent physical and functional characteristics and encompass objectified relationships among building components. Despite its benefits, BIM is mainly only used in the design phase (Tu et al., 2021). The main reason is that BIM is required to carry different information for different phases, and too much useless information will reduce users' willingness (Wang et al., 2022). Therefore, it is necessary to develop BIMs containing different information or to automate the addition or subtraction of BIM information for different usage requirements.

Digital models of cities usually referred to as City Information Models (CIM) or 3D city models, which need to consider topographical data such as mountains, rivers and buildings and infrastructure (Xia et al., 2022). Souza and Bueno (2022) have shown that CIM contains Geographic Information System (GIS) data and BIM data, as well as data collected by the Internet of Things (IoT) and sensors. It enables automatic management of urban information and predictive reasoning about urban problems. For example, as different regions and buildings in a city have different energy demands and consumption (Camero and Alba, 2019), CIM can help predict energy-associated problems ((Xia et al., 2022) (Weil et al., 2023)). Although CIM can present a wealth of information, CIM faces a similar problem as BIM: they both carry a wealth of information, which makes users who only need a specific piece of information reluctant to invest additional time and resources to get the information they need from it. In other words, the development of BIM/CIM with different information or the ability to automatically add or subtract information from BIM/CIM is a real need for most users. In BIM/CIM, 3D geometric models are critical primary data. To improve the user experience and meet different business requirements and application scenarios, developing digital models with different geometric levels or graphical simplification may be an effective way.

The same Digital models may have different levels of detail (LoD) in different application scenarios. LoD refers to the representation of a 3D model with different data information, mainly concerned with the geometric details of the graphics. In BIM/CIM, there is a similar concept of LoD, but it is not limited to graphical rendering but also includes other information (Deng et al., 2016). In the commonly used CIM data exchange format City Geography Markup Language (CityGML), LoD is not only the complexity of the geometrical level of the city model but also includes the complexity of the semantic information (Kolbe et al., 2005). The concept of LoD also exists in BIM. However, the current level of development (LOD) is more widely used than LoD, which was developed by the American Institute of Architects (AIA) as an improvement of LoD and started with five levels from LOD 100 to LOD 500 (Abualdenien and Borrmann, 2022), corresponding to the five phases of conceptualization, approximate components, exact components, construction, and completion. The BIMForum has further improved the AIA definition by developing a new LOD350 level and publishing the LOD Specification. In addition to defining LoDs with expert knowledge, it is also possible to adjust the LoDs of the model using some software, such as Blender and Unity, which can modify graphics details. Fig. 1 shows the result of representing the exact Monkey in Blender with a different number of surfaces.

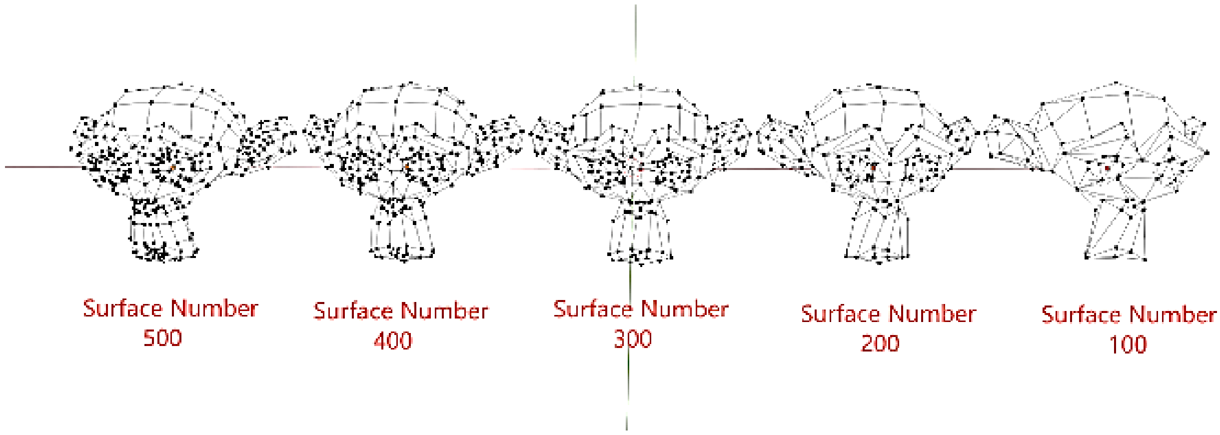

Figure 1: Blender generates a Monkey with different numbers of faces

Although some standards for LoDs exist, there still needs to be more clarity in understanding the information required for LoDs in different countries and organizations, especially concerning geometry. The main reason is that semantic information can usually be normalized into a set of attributes, but systematically examining the geometric details of a model, developing appropriate criteria to classify the hierarchy of geometries, and applying them to specific models is very difficult (Abualdenien and Borrmann, 2022). In addition, integrating the models of different LoDs into a city model is also a challenge. Table. 1 shows the LoD of BIM defined by AIA and the definition of LoD by CityGML

Table 1: LoD Definitions for BIM and GIS

LoD of BIM	LoD of GIS
LoD 100: Information on building height, area, and volume for conceptual design	LoD 0: Digital Elevation Model (DEM) and Digital Orthophoto Map (DOM) for regional landscape representation scale
LoD 200: Approximate information on generic elements for preliminary design	LoD 1: Block models at the city and regional representation scale
LoD 300: Detailed information on specific components for detailed design	LoD 2: Basic models at the district and street representation scale
LoD 400: Complete construction and installation information for the construction design	LoD 3: Standard models for representative building exteriors
LoD 500: Information on structural components corresponding to the as-built design	LoD 4: Advanced models for representative building interiors

Similar to this review, many scholars have reviewed and summarized the literature on BIM, GIS, Urban Digital Twin (UDT), and other themes related to digital modelling. Table. 2 shows some of the representative literature.

Table 2: A representative collection of literature reviews related to BIM/GIS/UDT

Articles	Main Contents
Wang et al., (2019)	It provided a review of BIM-GIS integration in sustainable built environments.
Jiang et al., (2021)	It identified recent advances in DT in civil engineering and made recommendations for future DT developments.
Khan et al., (2022)	It highlighted the challenges and future directions of multiscale modelling for megacities and intelligent cities.
Kamra et al., (2023)	It summarised techniques for lightweight city reconstruction and indicated future research directions.
Weil et al., (2023)	It summarised the main challenges and unresolved issues related to the implementation of UDT.

Compared to the representative literature review in Table. 2, this SLR focuses on the MSDM for buildings and cities. With the rapid development of information technology and the further expansion of urban boundaries, the demand for MSDM will skyrocket(Abualdenien and Borrmann, 2022). Therefore, an SLR is needed to inform scholars of the current research gaps on MSDM and more accurately capture future research priorities.

The rest of the paper follows: Chapter 2 introduces the methodology applied, describing the SLR protocol.

Chapter 3 shows the results obtained by SLR. Chapter 4 discusses the inspirations gained and points out future research priorities. Chapter 5 summarises the whole paper and further highlights the contributions made in this SLR.

Methodology

Searching database and keywords

The literature covered in this SLR is at the intersection of civil engineering and computer graphics. Since computer technology requires high timeliness and many scholars will publish their papers at conferences, this SLR needs to cover conference and journal papers. Four academic databases, ACM Digital Library, IEEE Xplore, Scopus, and Web of Science (WOS), were selected for searching. The ACM Digital Library and IEEE Xplore are critical academic databases for computer science, containing many conference papers and some journal papers related to computer graphics (Cheng et al., 2022). Scopus and WOS are more comprehensive in their coverage of the subject areas and contain more abundant journal papers (Srinivasan and Yadav, 2023) and, therefore, serve as a supplement to the ACM Digital Library and IEEE Xplore.

After determining the search database, this section will identify the search keywords. Considering that the core research question of this SLR is "Research on Building/City MSDM," this SLR divides the required keywords into two parts. Fig. 2 shows the complete search formula (four databases use a similar search logic).

Building modeling	City modeling
(“ifc” OR “industry foundation class*” OR “bim” OR “building information model*” OR “building model*” OR “building digital twin*”) **AND** (“Multiscale” OR “lod” OR “level of detail*” OR “log” OR “level of geometr*” OR “loi” OR “level of information”)	(“citygml” OR “city geography markup language” OR “cim” OR “city information model*” OR “cit* model*” OR “urban* model*” OR “town* model*” OR “cit* digital twin*” OR “urban* digital twin*” OR “town* digital twin*” OR “3D GIS” OR “3D geoinformation”) **AND** (“Multiscale” OR “lod” OR “level of detail*” OR “log” OR “level of geometr*” OR “loi” OR “level of information”)

Figure 2: Schematic diagram of the used search formula

Literature screening criteria

After reading the title-abstract-keywords of each piece of literature, literature duplicated or did not meet the research objectives was excluded, and the detailed literature screening criteria were as follows.

(1) Removing literature whose form of publication is not an article or conference paper (published as a book, magazine, etc.); (2) Removing literature whose language of publication is not English; (3) Removing literature in apparently unrelated subject areas (e.g., Nursing, Veterinary, Dentistry, etc.); (4) Removing literature that is purely theoretical, purely conceptual and not focused on digital modelling; (5) Removing duplicates. After obtaining all the powerfully relevant literature, further reading the full text and delineating the literature at both cities/buildings’ scales. Define the building scale as a single building or a component within a building and the city scale as multiple buildings or the integration of BIM with GIS.

Extracted information

After obtaining the required literature, further reading of the full text extracted more detailed information. The extracted information included the primary statistical information data of the literature. The following 12 categories of information were extracted: authors, affiliation of the first author, country of the first author's affiliation, date of publication, name of the journal or conference, keywords, purpose of the study, software or tool used, source of the data, format of the data, methodology of the study, and results of the study.

Results

Overview

Firstly, the initial search results were IEEE Xplore (123), ACM Digital Library (1316), Scopus (1655), and Web of Science (787), with a total of 3881 pieces of literature retrieved. Secondly, based on the screening criteria, 3881 pieces of literature were refined, resulting in 452. Then, the full text of 452 pieces of literature was carefully read, resulting in 45. Finally, the literature was divided according to the definitions of building scale and city scale. Twenty-four pieces of literature were obtained for the building, 21 for the city.

Research themes

Fig. 3 shows the application scenarios for city/building MSDM. In City management, there are main eight application scenarios. For Urban Renewal Synchronization, Qin, (2014) detected changes in the LoD2 building model using satellite-based stereo images from different dates. For Energy Demand Simulation, Nouvel et al., (2017) investigated the impact of data quality, such as geometry and semantics, on SimStadt's estimation of heating demand. The LoD1 model can reliably estimate the heating demand of an area, and the LoD2 model can reliably estimate the heating demand of a single building. De Jaeger et al., (2018) quantified the geometric and energy characteristics differences between the five variants of LoD1 and LoD2. It investigated the availability of LoD1 and LoD2 and the impact of building geometry in regional energy modelling. For Energy Consumption Simulation, Johari et al., (2022) analyzed the impact of LoD on energy use in different types of multifamily residential buildings. The effect of LoD was negligible in heating seasons, whereas it was significant throughout the year. The deviation between LoD1 and LoD3 was as high as 9%. For Solar Energy Simulation, Nahon et al., (2013) argued that using adaptive LoD speeds up calculations and ensures accuracy. Besuievksy et al., (2014) introduced a flexible LoD system that allows the user to specify the geometric hierarchy of geometric models for solar simulation. Besuievksy et al., (2014) estimated the annual solar irradiance of a building's roof using Monte Carlo simulation and conducted uncertainty analyses in different LoD models. Besuievsky et al., (2018) proposed a new LoD strategy that automatically detects and preserves the geometries (e.g., roofs) that affect the solar simulation. It simplified the rest of the geometries. Machete et al., (2018) evaluated the impact of the urban environment on the exposure of building roofs and facades to solar radiation by combining a 3D GIS with a solar radiation tool and using two different modelling approaches (2.5D and 3D methods). Peronato et al., (2018) simulated the solar irradiance of 109 buildings at different spatial and temporal granularities using the LoD2 model. Saretta et al., (2020) defined the LoD2.5 model to estimate the BIPV potential of a city containing facades. Han et al., (2022) predicted the regional power potential by analyzing the variation of shading effects between the LoD1 and LoD2 models. Krapf et al., (2022) extracted the roof superstructure from aerial imagery using deep learning, which can improve the solar simulation's accuracy. Yan et al., (2023) reconstructed three-dimensional buildings from high-resolution satellite imagery using a detail-oriented deep learning method and estimated the solar power potential. For Climate Simulation, Chen et al., (2020) cited 16 LoD models defined by Biljecki et al., (2016) for climate simulation.

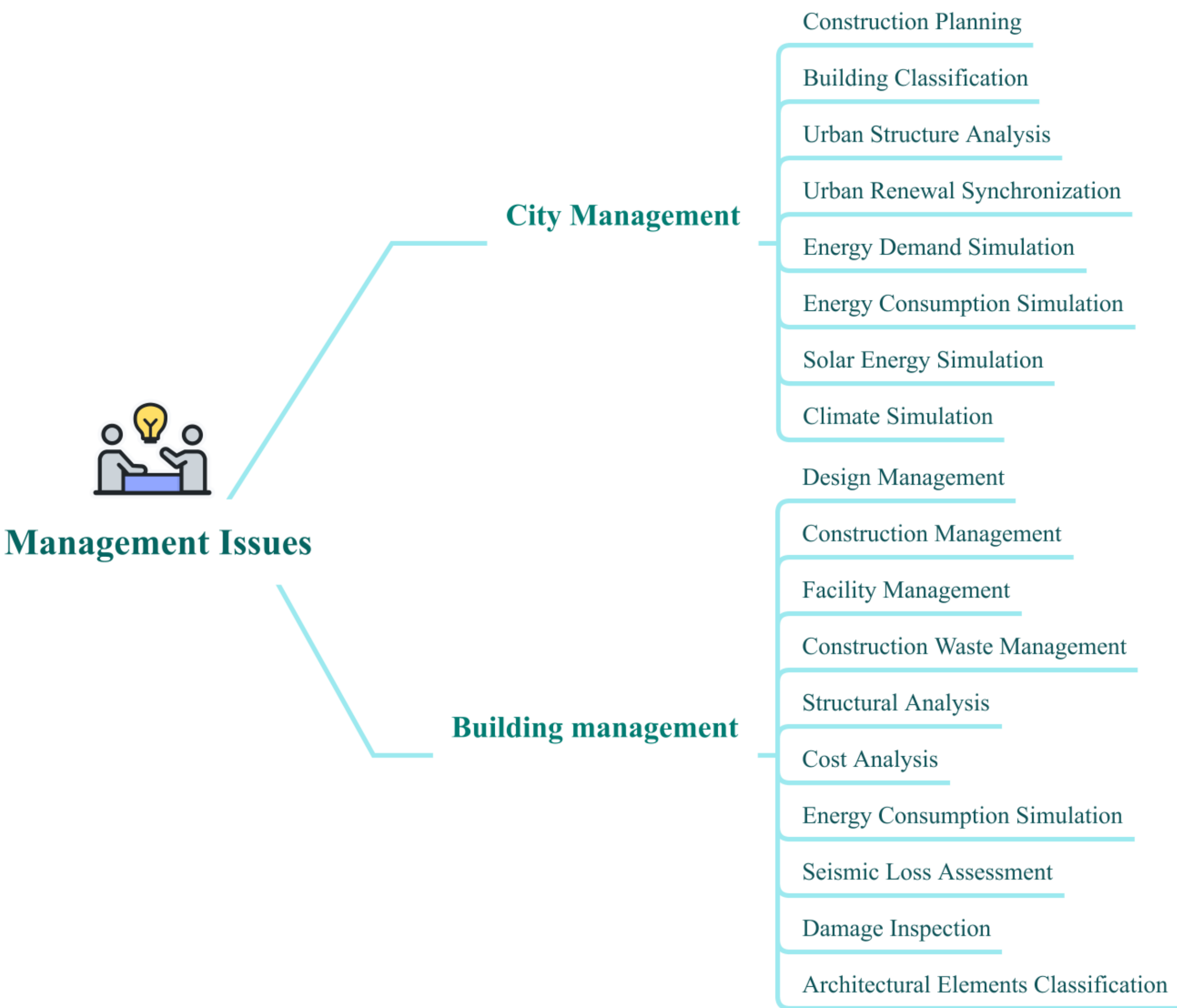

Figure 3: Application scenarios for city/building MSDM

In Building management, there are main ten application scenarios. For Design Management, Leite et al., (2011) evaluated the effort required to generate BIMs with different LoDs and the impact of LoDs on design coordination, such as electrical and plumbing (MEP). Huang et al., (2022) extended IFC to develop BIM models of metro stations with multiple LoDs, which can cope with different scenarios. For Construction Management, Han et al., (2015) enhanced the 4D BIM with lower LoDs to provide visual construction progress assessment for some projects. For Facility Management, Dias and Ergan, (2016) developed LoDs for facilities management. For Construction Waste Management, Sanchez et al., (2021) developed methods to automatically determine parameters that can be disassembled and defined BIM models and parameters for disassembly. For Structural Analysis, Briggen et al., (2009) used Computational Fluid Dynamics to predict Wind-driven rain volumes, concluding that façade geometric detailing significantly affects localization. Gonizzi Barsanti et al., (2023) obtained appropriate geometric detailing level models from the point cloud data, which can be used directly in finite element calculations. For Cost Analysis, Wood et al., (2014) enabled the automatic calculation of design costs by matching building material data with cost data on different LoDs. For Energy Consumption Simulation, Geyer et al., (2018) proposed a multi-LoD modelling approach combined with machine learning algorithms to predict energy performance. Malhotra et al., (2019) compared different LoDs and determined the LoDs required for heating load simulation. Singh and Geyer, (2020) analyzed the extent to which design parameters influence energy consumption prediction. It identified the information required for each level in a multi-LoD. Mediavilla et al., (2023) developed a methodology based on graph techniques for using multiscale BIM for energy analysis. Jung et al., (2023) proposed that LoD350 was suitable for modelling the energy performance of actual buildings. Xu et al., (2023) proposed a new LoD2 (LoD2ES) for energy simulation. For Seismic Loss Assessment, Xu et al., (2019) evaluated earthquake damage using BIM with different LoDs. For Damage Inspection, Pantoja-Rosero et al., (2023) constructed LoD3 BIM models for building damage assessment. For Architectural Elements Classification, Koo et al., (2021) classified IfcDoor and IfcWall using Multi-view CNN and PointNet. Abualdenien and Borrmann, (2022) proposed a framework for analyzing and checking the LoG of BIM.

In City/Building Management, energy issues are hot research themes. Scholars try to use different LoD models, combine different frameworks, and use different methods to predict the energy demand, consumption, and solar power generation potential. Scholars have already obtained valuable research results. However, many issues still need to be fully resolved due to the excessive number of factors and the complexity of the problem. There will remain a topic worthy of in-depth research.

Implication

Current researches

MSDM is for a better solution to practical problems. By this paper, it is clear that MSDM can serve all stages of the whole life cycle of a building, solving problems in all aspects of urban construction and maintenance, which contribute to the sustainable development of cities. However, there are still the following limitations in the current researches.

Much of the current literature on the application of MSDM to city management focuses on problems related to building groups. Although the problems addressed are relevant to individuals and societies, the boundaries of research should be further expanded. Scholars need to consider infrastructure and management issues further. MSDM is a substantial database for solving all kinds of problems in the city and society.

Future directions

MSDM has to serve practical problems. The above limitation is a direction that deserve research in the future, but the current most worthwhile research is to use MSDM to solve urban energy-related problems.

Excessive use of non-renewable energy sources (such as fossil fuels) may cause environmental and social problems. Widespread use of renewable energy in cities will contribute to sustainable urban development. Scholars have estimated the energy demand, energy consumption, and solar power generation potential of cities/buildings through various means of simulation. It contributes to energy management in cities and the development of urban distributed generation. However, there needs to be research on unifying these results in a single system or considering the optimal arrangement of solar power generation systems, energy storage systems, and the connection to buildings because most of the distributed energy generation in cities tends to be self-generated and self-consumed. Urban planners need to consider how to manage the excess renewable energy to respond flexibly to different situations. The potential for urban distributed energy generation should be combined with regional energy demand consumption to achieve a rational distribution of renewable energy sources. Fig. 4 shows the framework for future research on energy issues.

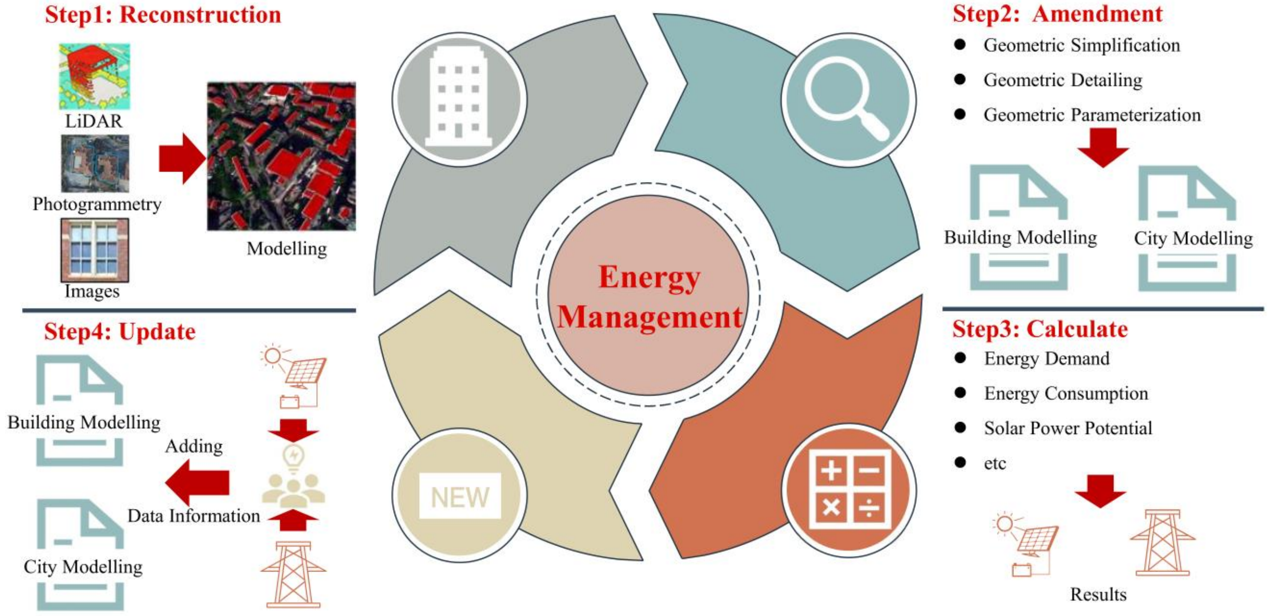

Figure 4: Research framework for future city energy management

Firstly, using LiDAR/Photogrammetry/Images to reconstruct the MSDM of the actual city. Secondly, using Geometric Simplification/Detailing/Parameterization to amend the MSDM. Then, based on the MSDM, calculate parameters such as the city's Energy Demand/Consumption and Solar Power Potential. Based on these results, developing algorithms to rationally plan the distributed energy generation system, energy storage system and the specific allocation of energy use in the region. Finally, the obtained information is fed back to the MSDM to update the MSDM to achieve sustainable urban energy management.

For researchers, LoD definitions for different scenarios and the level of detail provided can help designers identify potential problems early in the project, reduce errors and design modifications, and thus improve the design quality. It will help designers better understand and plan their projects, which will help optimise the use of materials and construction techniques and further reduce costs.

The conversion of models at different levels of detail can effectively facilitate collaboration between project participants by providing a shared, multi-scale project model. Different teams can work on the same model and view and update information in real time, significantly improving project collaboration's efficiency and effectiveness.

Conclusions

This paper presents a comparative analysis of the current advances in MSDM research from both city/building perspectives. Compared to previous literature reviews, this review focuses on the different scales of digital models, especially their geometric aspects. This paper identifies the research themes of MSDM for cities/buildings, analyses the findings of the existing literature by theme, and points out the hot research themes in "City/Engineering Management" and the limitations of each research theme. Regional energy management will be one of the hot research directions, based on MSDM, to unify distributed energy generation system - energy storage system - building/infrastructure in one system will achieve the optimal distribution of energy, give full play to the potential of renewable energy, and promote the sustainable development of the city and the society.

Furthermore, this paper finds that scholars in Africa and South America are not concerned with MSDM research, much less using MSDM for energy management. The equatorial region is extremely rich in solar energy resources. From a global energy perspective, it is necessary to apply the research results of MSDM in equatorial countries to enhance global energy sustainability further.

However, this paper still has some limitations. Only a representative portion of the literature selected for this paper and other valuable literature may have yet to be analysed. Meanwhile, the search terms may need to be more comprehensive, and some may need to be complete.

Acknowledgments

The authors would like to acknowledge the financial support provided by the National Natural Science Foundation of China (Grant No. U21A20151).

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