Automation in Construction 152 (2023) 104934

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Review

Applications of Building information modelling in the early design stage of high-rise buildings

Hossein Omrany [a], Amirhosein Ghaffarianhoseini [b], Ruidong Chang [a], Ali Ghaffarianhoseini [b], Farzad Pour Rahimian [c,*]

[a] School of Architecture & Built Environment, University of Adelaide, Adelaide, Australia
[b] Department of Built Environment Engineering, School of Future Environments, Auckland University of Technology, Auckland, New Zealand
[c] School of Computing, Engineering & Digital Technologies, Teesside University, Middlesbrough, UK

ARTICLE INFO

Keywords:
BIM
High-rise buildings
Building energy efficiency
Building energy optimisation
Collaborative design

ABSTRACT

High-rise buildings consume more energy and have greater environmental impacts, emphasising the need to adopt best practices during the design stage concerning BIM employment. However, despite strong support from the literature, little is known about the applications of BIM in high-rise buildings at the early design stage. Therefore, this paper aims to provide a holistic understanding of the current applications of BIM in high-rise buildings by analysing 60 studies. The findings identified seven research themes, including studies that used BIM for i) optimising building energy efficiency design; ii) collaborative design and planning; iii) life-cycle assessment; iv) designing net-zero energy buildings; v) integrating BIM with smart technologies for designing high-rise buildings; vi) cost analysis, and vii) structural design of high-rise buildings. Furthermore, this study highlights a number of challenges hindering the widespread application of BIM, alongside providing potential directions for the future development of BIM employment in high-rise buildings.

1. Background

The recent report by International Energy Agency introduced the building sector as one of the main contributors to global energy consumption and carbon emissions in 2021 [1]. Based on this report, the total final energy use in buildings increased from 115 Exajoule in 2010 to approximately 135 Exajoule in 2021 worldwide [1]. This constitutes the overall shares of the building sector in global energy consumption and total carbon emissions of 30% and 27%, respectively [1]. This is largely driven by the increasing world population and its attendant effects on growing demands for energy, followed by improving access to energy in developing countries, greater ownership and use of energy-consuming appliances, and rapid migration to cities [1]. The energy consumption in the building sector is also expected to increase further in the next decades due to the growing world population. The United Nations projected that the world's population would increase by 2 billion in the next 30 years, e.g., from 7.7 billion to 9.7 billion by 2050, reaching nearly 11 billion by 2100 [2]. Therefore, the impending challenge would be the development of enough settlements in the next decades to accommodate the increasing world population. This may become even more serious for countries where land scarcity is already a pressuring challenge. In this regard, one of the viable measures to tackle this challenge is to construct high-rise buildings.

Many descriptions have been presented to characterise high-rise or tall buildings [5,7]. In one of the well-established definitions given by the Council on Tall Buildings and Urban Habitat (CTBUH), high-rise buildings are defined as those with more than 14-storeys (or with heights over than 50 m and less than 300 m), while buildings with heights more than 300 m and 600 m are considered as "super-tall" and "mega-tall", respectively [3]. Amid the heated debates for reinforcing sustainable development and urban compactness, combined with the housing urgency and the arrival of new technologies, the interest for residing in high-rise buildings is increasing. Currently, approximately 36 million European households live in high-rise buildings, i.e., one in six of all households [8]. In Asia, Hong Kong and Singapore are distinguished by their high-rise public housing developments. Based on the data published by CTBUH, there are currently 6588 buildings with heights of more than 150 m; 2006 buildings with more than 200 m, and 204 buildings with over 300 m worldwide [9]. These buildings are constructed in over sixty countries. Among all, China has the highest

* Corresponding author.
E-mail address: f.rahimian@tees.ac.uk (F. Pour Rahimian).

https://doi.org/10.1016/j.autcon.2023.104934
Received 18 January 2023; Received in revised form 13 March 2023; Accepted 5 May 2023
Available online 11 May 2023
0926-5805/

number of high-rise buildings in the world with more than 4100 buildings that are over 150 m, followed by the U.S., South Korea, and UAE (Fig. 1) [9]. With almost half of the world population living in urban areas, the unfolding trend is towards a more urban-style development with taller buildings being considered as an inevitable housing solution in the future.

High-rise buildings are known to be more energy-consuming with greater environmental impacts. This is echoed in the findings of Steadman [10] that investigated the carbon emissions and electricity use of 610 high-rise and low-rise office buildings in the UK. The findings revealed that high-rise buildings' electricity usage and carbon emissions were higher than low-rise buildings by two and a half times and two times, respectively. This is aligned with the findings of Godoy-Shimizu et al. [11] that analysed the association between operational energy use and the height of 611 office buildings in England and Wales. The results showed that increasing buildings' height from five storeys and below to 21 storeys and above led to increasing the mean intensity of electricity and fossil fuel usage by 137% and 42% respectively, while the mean carbon emissions can be more than doubled. The increase in energy use of high-rise buildings can be related to the higher exposure of high-rise buildings to lower temperatures, stronger winds and more solar exposure, as suggested by Godoy-Shimizu et al. [11]. The higher capacity of tall buildings for energy consumption underlines the need of adapting best practices during the design stage to minimise energy use and environmental impacts of high-rise buildings throughout the entire buildings' lifecycle. In this regard, building information modelling (BIM) is an auspicious approach that has appeared strongly over the recent decades to support decision-making during the design stage of project lifecycle [12,13].

The concept of BIM is an overarching term used to characterise various activities in object-oriented Computer-Aided Design (CAD), aiming to provide a better representation of geometric and non-geometric (e.g., functional) attributes of building elements as well as their associated relationships [12–14]. Adopting BIM in the architecture, engineering, and construction (AEC) industry has proven effective in enhancing inter-organisational collaborations while contributing to the bettering design, construction, and maintenance practices across the industry [12]. The initial utilisation of digital tools can be traced back to the 1970s when 2D designs were used to share architectural plans via CAD. Still, only in the early 2000s did the concept of BIM gain momentum [12]. The BIM models created possibilities for incorporating informational textures associated with objects (e.g., construction materials) into the functional designs developed by practitioners [4,12].

Nowadays, BIM is regarded as a promising solution to facilitate the management and integration of project information throughout the entire project lifecycle [12], thus assisting with optimising the use of design data for buildings' performance analysis and realising sustainable designs [15]. The definition of BIM may vary depending on the model's content, its application, and also the analysis set to be carried out. The U. S. national BIM standard comprehensively defines BIM as the process of developing digital models of a given facility aiming to visualise, and perform engineering analysis, conflict analysis, compliance code checking, cost engineering, as-built product, and budgeting [16]. In another definition, Smith and Tardif [17] defined BIM as a mechanism to transfer data into information with the purpose of generating knowledge that further enables users to make informed decisions. Sackey et al. [18] described BIM as a socio-technical system due to its characteristics which are composed of both technical dimensions such as 3D modelling, and aspects with social impacts such as process re-engineering. Therefore, BIM is a multi-layered concept providing a shared data repository that can effectively support decision-making throughout the project lifecycle. This study aims to explore the current applications of BIM during the early stages of building design, looking closely at the current exploitations of this approach for the delivery of high-rise buildings.

1.1. Motivation for this research

Due to the increasing BIM popularity, considerable research has been carried out investigating the use of this approach for different purposes in high-rise buildings. For instance, studies employed BIM for improving the management practices in construction projects [19–23], such as identifying uncertainty sources that may affect offsite logistics of modular construction in high-rise buildings [20], improving engineer-to-order materials flow management [21], optimising the measurement of construction progress in high-rise buildings [23], or evaluating structural safety and integrity of high-rise buildings [24]. Another stream of research utilised BIM for land administration purposes in high-rise buildings [25,26]. For instance, Atazadeh et al. [25] showcased the capacity of BIM for recording and representing information related to ownership and boundaries of properties. The application of BIM for enhancing safety during the construction of high-rise buildings is another popular area of research that has been the subject of various investigations by previous studies [27–32]. An example can be the study carried out by Manzoor et al. [27] who proposed a BIM-based framework for mitigating construction accidents in high-rise building projects.

Despite the flourishing interest in using BIM for performance analysis and design optimisation of high-rise buildings, no study has been conducted to solidify the current body of knowledge in this area by reviewing the relevant literature. Several review papers have investigated measures for improving energy savings in high-rise buildings [4,5,7,33]. For example, Mostafavi et al. [5] conducted a scoping literature review to study high-rise buildings' energy and carbon performance. To this end, they analysed 48 studies published between 2005 and 2020 in different climates. They realised there is a significant potential for energy savings in high-rise buildings by improving envelope

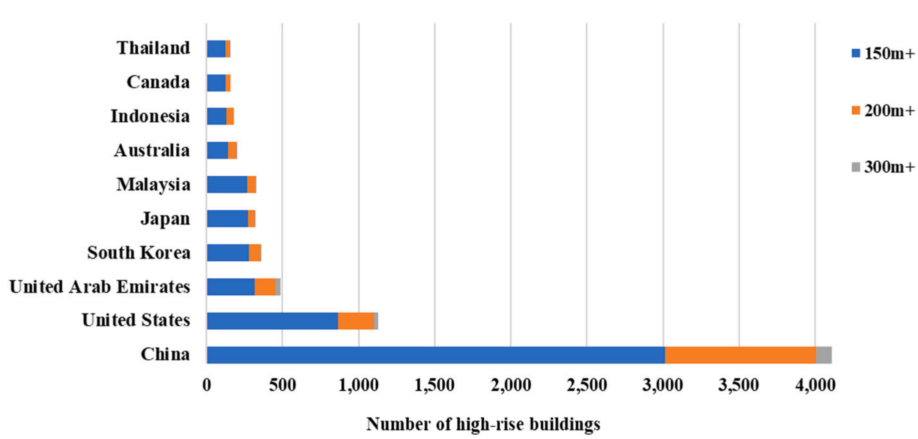

Fig. 1. Top ten countries with highest numbers of tall buildings. Sourced from CTBUH [9].

design parameters, optimising plan layouts, and employing natural ventilation. Analogously, Mirrahimi et al. [34] studied design parameters affecting energy savings for high-rise buildings in hot and humid climates and recommended considering optimal window-to-wall area and proper glazing systems and integration of the right shading devices to realise high energy savings in high-rise buildings. Wang et al. [7] also examined the role of high-rise residential buildings in enabling the low-carbon transition and improving the resilience of urban energy systems by reviewing retrospective studies. In another research, Wardahni et al. [33] reviewed e-maintenance elements and indicators influencing the maintenance performance of high-rise buildings. Cai et al. [4] also explored using construction automation and robotics for high-rise buildings.

Nevertheless, the current body of literature remains fragmented when understanding BIM implementations at the early design stage of high-rise buildings. The decisions made at the early stages of building design will have profound impacts on the final performance of a building, influencing its operational costs, energy, and environmental performance [12,125]. Therefore, the moral decisions made at this stage can potentially increase the chance of buildings meeting high-performance goals [12,125]. However, the current review studies are largely focused on soliciting strategies that help to reduce energy consumption and carbon emissions in tall buildings, whereas the current applications of BIM in coordinating the design development of high-rise buildings are overlooked. Therefore, the current paper aims to address this gap by providing a holistic understanding of the current BIM applications during the early stages of high-rise building design. Notably, the scope of this study is limited to investigating the use of BIM at the design stage; thus, studies that applied BIM at other stages of the building lifecycle (e.g., construction) are excluded.

The outcomes of this paper can be of interest to targeted groups by offering new insights into different ways BIM can possibly be deployed to assist with designing and planning high-rise buildings. This research also underlines some challenges hindering the widespread employment of BIM in high-rise structures, along with recommending solutions to overcome the identified challenges. Hence, future studies can rely on the results of this paper as a point of reference for further development of the field. The remainder of this paper unfolds as follows: the research methodology employed by this paper is explained in Section 2, followed by reporting the results of the analyses provided in Section 3. Section 4 offers a discussion on the common approaches adopted by the reviewed studies for applying BIM, introducing some challenges and providing recommendations for future development of BIM in high-rise buildings before conclusions are given in Section 5.

2. Research methodology

The overall methodological approach of this study consists of three main stages, as illustrated in Fig. 2. The first stage involved developing a search string that could capture publications relevant to this study's scope, aim and objectives. To this end, a search string was designed only to capture scholarly materials related to "high-rise buildings". Thus, the following syntax was constructed and employed for the retrieval of publications: (("high rise buildin*" OR "multi-storey build" OR "tall buildin*" OR "apartment tower" OR "residential tower" OR "apartment block" OR "block of flats" OR "office tower" OR "Skyscraper")).

The search was carried out through two main scholarly databases, including "Web of Science" and "Scopus" and it returned 647 materials on the 10th of November 2022. Afterwards, many exclusion criteria were considered for weeding out materials falling beyond the scope of

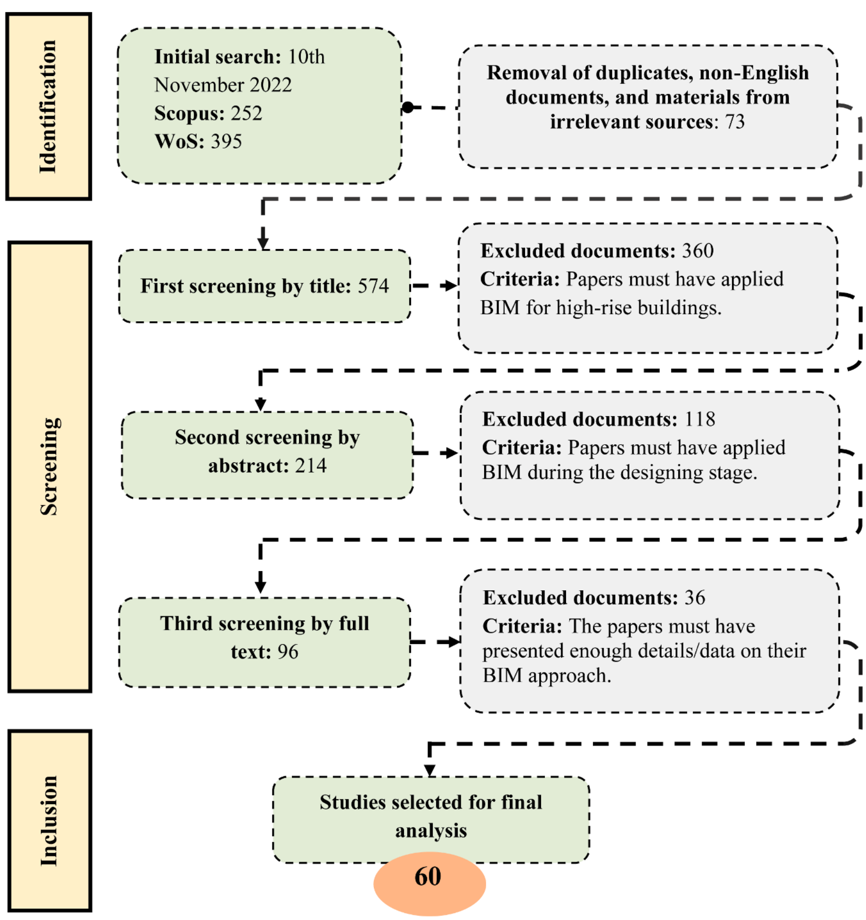

Fig. 2. Overall methodological approach of this study.

this study. First, publications written in non-English languages were filtered. Further, resources unrelated to building science (e.g., recourses belonging to law, medical science, agriculture, nursing, parasitology, or fisheries) were excluded via filtering functions of the Web of Science and Scopus. Considering these criteria led to omitting 73 materials identified in the initial search.

After that, the papers' titles were screened, and 360 publications were found irrelevant. The primary selection criterion considered at this stage was that all the materials must have used BIM for high-rise buildings. This was followed by performing the second screening measure in which studies must have applied BIM at the designing stage of high-rise buildings. For instance, publications that used BIM during the construction or end-of-life stages were excluded from further analysis. Consequently, this resulted in phasing out 118 papers. Finally, a full-text reading exercise was conducted on the shortlisted materials to ensure only studies that presented enough details about their adopted BIM approach/methodology were selected. Therefore, 60 publications aligned perfectly with this paper's scope and objectives were eventually selected for detailed examinations. These materials were thence exported in a Microsoft Excel Spreadsheet in order to carry out the content analysis. The obtained information related to each paper was extracted and synthesized to report the results provided in the next section. This study also conducted a keyword co-occurrence analysis to provide a better understanding of the thematic focus of the analysed literature. To this end, VOSviewer software which is an open-access software tool for bibliometric analysis was applied [35]. This is noteworthy to mention that designing, consultation, and construction firms use BIM for designing high-rise buildings. Nonetheless, their approaches or uses of BIM for such purposes are not published in scholarly papers, hence the current paper relies only on academic sources for carrying out the analysis.

3. Results and analysis

Fig. 3 presents an overview of the 60 analysed papers concerning the countries where the studies were carried out and their corresponding climates based on the Köppen classification. As can be seen, 45% of studies were conducted on cases in China and Hong Kong. This is consistent with the data published by CTBUH [9], which also introduced these countries as the ones currently having the highest number of high-rise buildings in the world. This is followed by South Korea and Canada with six and four studies that applied BIM for investigating high-rise at the early stage of project lifecycle, respectively. Most of the analysed studies were done in Cwa (26%) (humid subtropical climate), Cfa (21%) (warm temperate climate), and Dwa (12%) (humid continental climate). These findings indicate that BIM has a great potential for further research in regions where high-rise buildings are already a common norm in construction (e.g., Thailand, UK, or Australia). Regarding building type, 46% of the analysed studies were residential, while multifunctional facilities and office buildings constituted 17% and 13% of the selected studies, respectively. In addition, 7% of the studies did not explicitly disclose the type of buildings subjected to investigation and 17% of reviewed papers were miscellaneous buildings such as institutional, museum, university, and hotel buildings. The analysis of selected studies also revealed that 40% of the cases were buildings with 15 to 30 storeys, 29% of cases had 31 to 60 storeys and 14% were over 60 storeys. Moreover, 17% of the reviewed papers did not mention the number of buildings' storeys.

The results of keyword co-occurrence analysis are used (Fig. 4), in tandem with the authors' knowledge and judgments to classify the 60 selected papers into seven research themes. This classification is based on the main factors associated with BIM applications in high-rise buildings reflected in the reviewed papers (Fig. 5). As such, the current analysis is carried out based on the following themes: optimisation of building energy efficiency design, application of BIM for collaborative design and planning, life-cycle assessment, the realisation of net-zero energy buildings (NZEB), integration of BIM with smart technologies for designing high-rise buildings, the use of BIM for cost analysis and structural design of high-rise buildings. The following sections discuss each area of the BIM application in further detail.

Countries	No. of publications
Hong Kong	15
China	12
South Korea	6
Canada	4
Greece	2
Malaysia	2
Singapore	2
UK	2
Algeria	1
Australia	1
Chile	1
Egypt	1
Germany	1
India	1
Iran	1
Israel	1
Japan	1
Netherlands	1
Qatar	1
Thailand	1
Turkey	1
UAE	1
US	1

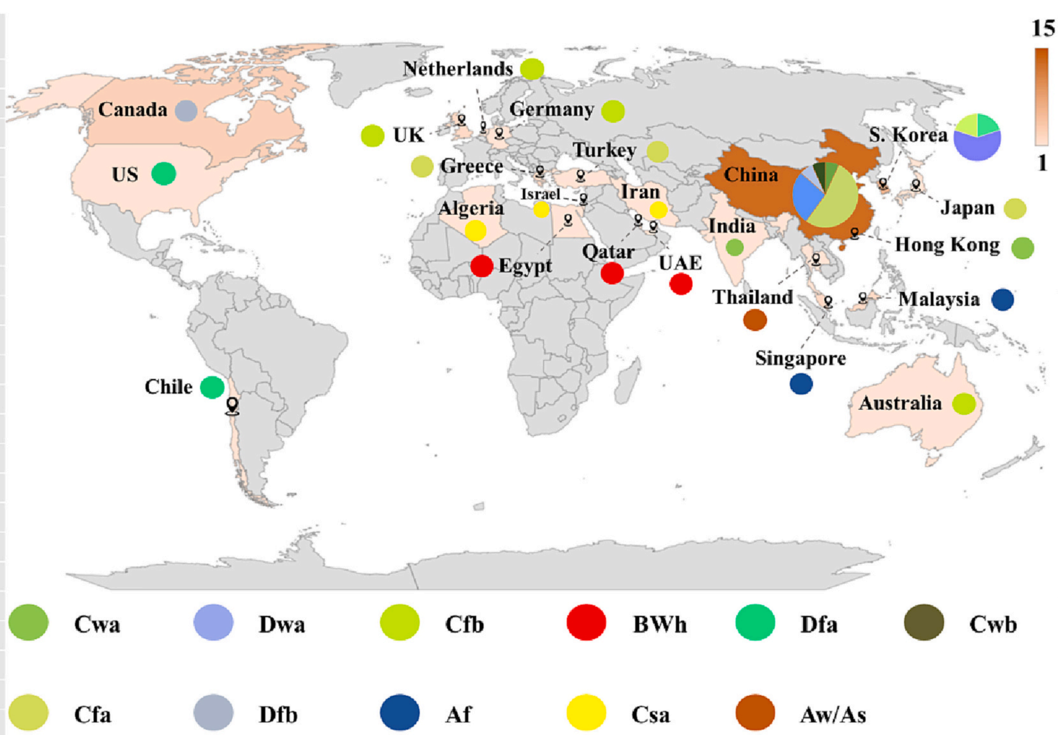

Fig. 3. Countries of reviewed studies and their corresponding climates based on Köppen classification.

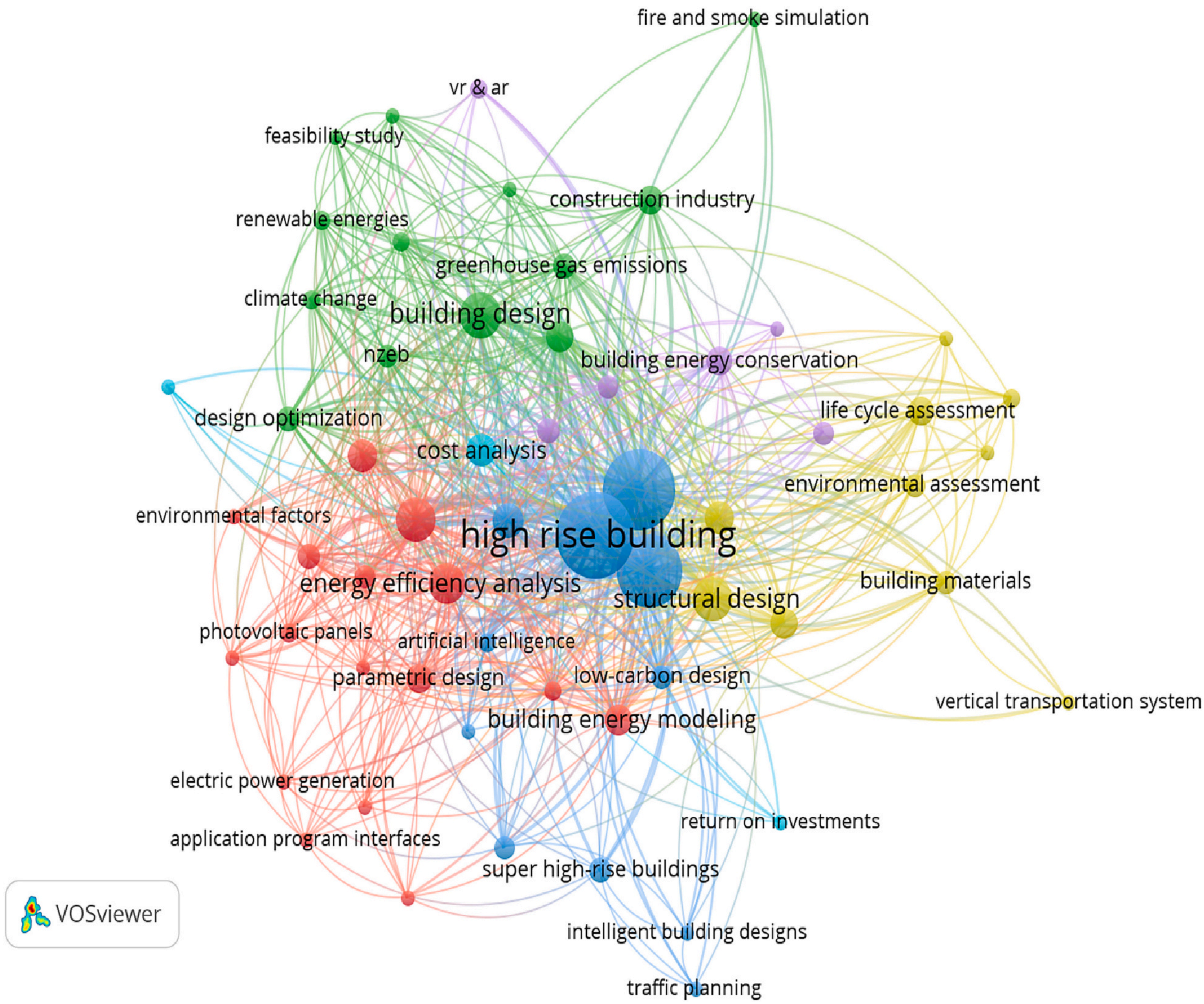

Fig. 4. Result of keyword co-occurrence analysis.

3.1. BIM for optimisation of building energy efficiency design

The analysis showed that 43% of the reviewed studies employed BIM to optimise high-rise buildings' energy efficiency performance (Table 1). The measures adopted by these studies to increase energy savings and minimise carbon emissions associated with building designs can be categorised into three groups: building envelope, mechanical and natural ventilation, and occupants' behaviours.

The building envelope establishes the interface between indoor and outdoor environments. Hence it can play a critical role in determining the energy performance of buildings [36,37]. The literature is enriched by studies investigating possibilities for increasing buildings' energy performance via improving envelopes [36,38]. The findings of this paper also indicate that reviewed studies endeavoured to enhance the overall energy performance of high-rise buildings by adopting various strategies to optimise different features of building envelopes. As indicated in Table 1, these strategies can be clustered into two groups including designed-related and construction-related. The former includes i) window features [39–47] (e.g., U-values, glazing types, location, orientation, and window-to-wall ratio (WWR)), ii) integrating shading systems [40–42,45,46], iii) building geometry and shape coefficient [44,48], iv) colours of external surfaces [40], and v) considering climate conditions [49]. The construction-related strategies employed by the reviewed studies include i) the use of double skin façade (DSF) [50,51], and ii) thermal insulation for exterior walls [40,42,44]. The results reported by the reviewed studies underline the considerable improvements achieved in the energy performance of high-rise buildings by optimising building envelopes. For instance, Ahrize et al. [52] deployed Autodesk Ecotect analysis software to assess the suitability of using DSF for minimising energy usage in high-rise office buildings located in hot and dry climates. The results pointed out that the application of this façade can potentially reduce energy consumption related to heating and cooling by 28% and 53.5%, respectively. In another study, Raji et al. [45] used DesignBuilder simulation software to investigate possibilities for improving energy efficiency of high-rise office buildings in the Netherlands. The results indicated that 42% energy-savings can be achieved in the total buildings' energy performance by optimising envelope features (e.g., glazing type, WWR, shading device and roofing system).

The selection of ventilation systems for high-rise buildings is of utmost importance owing to the direct influence of these systems on buildings' energy performance. The integration of ventilation systems, however, involves certain complications such as the stack effect which makes the assessment process for selecting a ventilation system in tall buildings complicated in comparison with other types of buildings. Therefore, ventilation has been the subject of many investigations by previous studies, as also reflected in the findings of this paper (Table 1). In this regard, using BIM at the design stage assists decision-makers with selecting a ventilation system that can improve buildings' energy efficiency without compromising occupants' comfort. For instance,

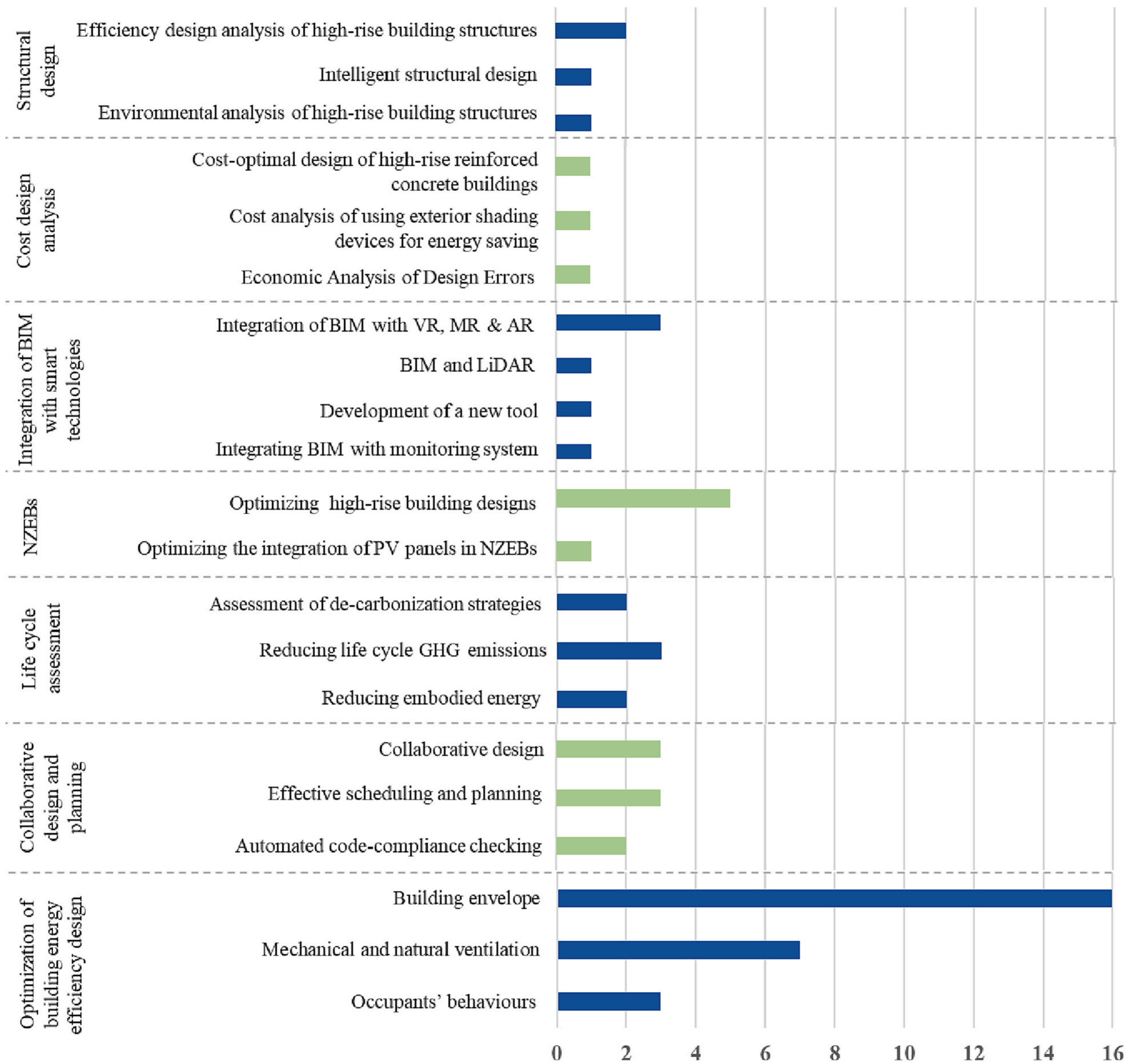

Fig. 5. Classification of papers based on their research themes.

Prajongsan, and Sharples [60] assessed the potential of using ventilation shafts in high-rise residential buildings in Bangkok to increase energy savings and thermal comfort of occupants. To this end, a CFD analysis technique was used by employing the CFD package of the DesignBuilder modelling software. The results showed that applying a ventilation shaft can facilitate the provision of natural ventilation, thus improving the thermal comfort of occupants by 56% and achieving energy savings of approximately 2700 kWh. In another study, Weerasuriya et al. [56] proposed a BIM-based framework to evaluate the potential of using natural ventilation in residential high-rise buildings. The framework was composed of CFD simulation, multi-zone-air-flow modelling, and building energy simulation engine which enabled calculating ventilation rates under the mechanisms of wind-, buoyancy- and wind and buoyancy-driven ventilation. The simulation results showed that electricity consumption could be minimised by 25% and 45% when the building was equipped with wind-driven natural ventilation and buoyancy-driven natural ventilation, respectively.

BIM-related tools have increased to leverage improving the decision-making process across the building sector. Nevertheless, there has been some discrepancy between the actual performance and the simulated results of building performance. This inconsistency, also the so-called performance gap, may stem from multiple sources such as occupants' behaviours, weather deviations, and differences between design vs. as-built drawings [65,66]. Shi et al. [67] found out that the significance of performance gap could be differing by a factor between 0.2 and 4.0. This discrepancy may subsequently affect the process of decision-making. Regarding occupants' behaviours, the majority of current tools describe occupants' presence and their actions as homogeneous and passive agents whereas they are diverse agents and actively interact with the building and its associated systems [67]. Therefore, studies endeavoured to find effective solutions for incorporating occupants' behaviours into the simulation tools [65,66]. The findings of this review also identified a number of studies that highlighted the importance of occupants' behaviours in estimating high-rise buildings' performance [62–64]. For instance, Jang and Kang [63] developed a stochastic model with a consideration of occupant random behaviours for using heating and electricity in order to reflect on the variations in actual energy usage in high-rise buildings. The results suggested that using the proposed model can mitigate uncertainties attributed to building simulations.

Table 1
Summary of studies that used BIM for improving energy efficiency in high-rise buildings.

Authors	Locations	Areas of focus	Research approach/applied tools	Findings
		Building envelope		
Raji et al. [45]	Delft, Netherlands	Exploring design alternatives for increasing energy performance of building envelopes via sensitivity analysis.	DesignBuilder software was used to perform sensitivity analysis.	42% energy-savings achieved for total building energy use performance by optimising glazing type, WWR, shading, and roofing systems.
Saroglou et al. [51]	Tel Aviv, Israel	Tested the efficacy of DSF external wall for energy savings in a high-rise building located in the Mediterranean climate.	EnergyPlus plugin of Google SketchUp was used to simulate mechanical and natural airflow within the cavity of DSF.	The results showed that cooling loads can be decreased significantly when cavity width increased from 0.2 m to 0.5 m; from 0.5 m to 1.0 m, and from 1.0 m to 2.0 m.
Ali et al. [46]	Kuala Lumpur, Malaysia	Optimising features of windows, e.g., glazing, opaque materials, and shading elements.	Simulation approach was adopted using ArchiCAD software.	3% to 6% improvements in cooling loads were achieved by enhancing infiltration rate and heat transfer coefficient.
Zhao et al. [53]	Hong Kong	Modelling carbon emissions associated with high-rise buildings.	First, the main challenges related to carbon emissions identified, and then implications for building design decision making were examined via simulation.	Identification of several challenges facing practitioners when using BIM for simulating carbon emissions in high-rise buildings.
El-Agami et al. [48]	Seven cities in Egypt	The effects of building' geometry on energy consumption of high-rise buildings were investigated in seven Egyptian cities.	EnergyPlus simulation engine integrated in DesignBuilder was used.	The finding suggested that the most compact building shape, e.g., circular, was the most suitable geometrical shape.
Ahrize et al. [52]	Algiers City, Algeria	Investigated the use of DSF for improving energy efficiency of high-rise buildings in hot and dry climate via sensitivity analysis.	Autodesk® Ecotect® Analysis software was used to model computer simulations.	The results showed that the use of DSF can reduce heating and cooling energy usage by 28% and 53.5%, respectively.
Yu et al. [44]	Four cities in China	The impacts of envelope design parameters (e.g., thermal insulation, shape coefficient, and WWR) on energy consumption were assessed in four cities with hot summer and cold winter.	Sensitivity-based simulation analysis approach was used.	The most important design variables with impacts on energy usage during hot and cold seasons were identified.
Yaşar and Kalfa [43]	Trabzon, Turkey	The impacts of window types (e.g., tinted, clear reflective, low emissivity, and smart glass) on the energy use of high-rise buildings were investigated.	DesignBuilder simulation software was used to estimate the energy use for each window type.	The results showed that smart-glazed units and low-emissivity glazing were the most energy-efficient alternatives.
Yoon et al. [50]	Daejeon, South Korea	The use of a DSF system for optimising the thermal performance of high-rise buildings.	EnergyPlus simulation software was used to analyse the energy performance of the building.	The results showed that 30% of energy savings can be achieved.
Al-Tamimi and Fadzil [42]	Penang, Malaysia	Analysing the impacts of building envelope design parameters (e.g., area ratio of window to wall, exterior wall thermal insulation, glazing, and shading systems) on energy consumption of high-rise buildings.	Ecotect software was applied.	The results suggested that the use of thermal insulation in external walls was the best strategy which led to reducing 10.2% and 26.3% in cooling energy load and peak cooling loads, respectively.
Wang et al. [41]	Singapore	Optimisation of facade designs (e.g., U-values, orientations, WWR, and shading device lengths) for better indoor thermal comfort and energy saving in Singapore.	Parametric design analysis was done using ESP-r and FLUENT software tools.	The most optimum U-values for windows located in the north and south orientations and optimum WWR were recommended for naturally ventilated residential buildings in Singapore.
Bojic et al. [39]	Hong Kong	Using different glazing types (e.g., clear glazing, tinted glazing, reflective glazing, and tinted and reflective glazing) for reducing annual cooling loads and the peak cooling loads of high-rise residential buildings in the hot and humid climate of Hong Kong.	HTB2 simulation software was used.	The results suggested that the maximum decrease of 13% and 16% in yearly cooling load and the peak cooling load were reported, respectively, for a case equipped by the tinted, reflective glazing that faced south.
Huang et al. [54]	Jining City, China	The energy-saving potentials of passive strategies (i.e. U-values of external walls, windows, roofing system, and ground floors) were assessed.	DesignBuilder software was used.	The results showed that the total buildings' energy usage can be reduced by 78.9%.
Cheung et al. [40]	Hong Kong	The use of passive design strategies (i.e. insulation, the colour of external walls, glazing systems, WWR, shading devices) for improving the energy efficiency of high-rise buildings.	TRNSYS simulation software was used.	31.40% of saving in annual cooling energy and 36.80% in the peak cooling load were achieved by using passive strategies.
Ma et al. [49]	Hong Kong	The impact of meteorological factors on the energy consumption of high-rise office buildings was investigated.	Fifty-seven runs of EnergyPlus simulations were performed based on 30 years of actual hourly meteorological data between 1989 and 2018 to evaluate the impacts of buildings' energy usage on climate change and urban heat island effects.	The results suggested that the energy consumption of high-rise office buildings in Hong Kong was more sensitive to changes in temperature and moisture in hot and humid than in cold and dry conditions.
Kahsay et al. [47]	Boston, US.	Proposed a BIM-based framework for optimising window configurations (e.g., window size and room location) of a high-rise building to minimise its energy consumption.	Integration of CFD and energy simulation.	Optimum window configurations were identified using the developed framework for the 2nd, 15th, and 29th floors.
		Mechanical and natural ventilation		
Sha and Qi [55]	Montreal, Canada	Examined the energy-saving potentials of using mechanical ventilative cooling systems in high-rise buildings.	Various energy-saving approaches were modelled including the use of optimal control methods, using energy-efficient fans, and increasing nominal fan flow rates.	The results suggested that the use of energy-efficient fans, combined with employing optimal control methods and increasing the

(continued on next page)

Table 1 (*continued*)

Authors	Locations	Areas of focus	Research approach/applied tools	Findings
		Building envelope		
				nominal ventilation flow rate can achieve energy-savings for cooling.
Weerasuriya et al. [56]	Hong Kong	The potential of natural ventilation for reducing energy usage in high-rise buildings was investigated.	A BIM-based framework was developed by integrating Computational Fluid Dynamics (CFD) simulation, multi-zone-air-flow modelling, and building energy simulation.	The results indicated the capacity of the proposed framework for measuring energy-savings that can be achieved by using wind-driven natural ventilation and buoyancy-driven natural ventilation.
Gan et al. [57]	Hong Kong	An energy performance-based optimisation approach was developed to identify the energy-efficient layout plan design for high-rise residential buildings.	An evolutionary genetic algorithm was developed to find the best layout designs for maximising the building's energy efficiency.	The total energy use of the building was minimised by 30–40% by increasing the utilisation of wind-driven natural ventilation and sunlight.
Moujahed et al. [58]	Lusail City, Qatar	The most influential parameters in the energy consumption of high-rise buildings were identified.	Building models were established using OpenStudio® and EnergyPlus tools, and then a Global Sensitivity Analysis method was used to find the most important parameters that affect the building's energy use.	Cooling setpoint, outdoor air requirements, equipment power density, and lighting power density were the most important factors contributing to the energy usage of high-rise buildings.
Yang and Li [59]	Chongqing, China	Providing optimum ventilation flow rates for all the floors of a multi-story building.	A stack-based hybrid ventilation scheme consisting of "naturally ventilated floors" and "mechanically ventilated floors" was proposed.	The developed scheme showed promising results in increasing energy efficiency for multi-story buildings.
Prajongsan, and Sharples [60]	Bangkok, Thailand	Improving natural ventilation and thermal comfort in tall buildings in Bangkok by employing ventilation shafts.	The CFD analysis was carried out using the CFD package of DesignBuilder software.	Results indicated the improvement of both thermal comfort and energy-savings due to using a ventilation shaft.
Alnusairat and Jones [61]	London, UK	Investigated the potential of using Skycourt as a ventilated buffer zone for office buildings in a temperate climate.	Building energy simulation tool, e.g., HTB2 software, was coupled with CFD software, e.g., WinAir.	The integration of Skycourt created free-heated and free-cooled buffer zones, reducing energy usage by more than 55%.
		Occupants' behaviours		
Qin and Pan [62]	Hong Kong	The impacts of various energy-saving measures for achieving very low-energy high-rise buildings in subtropical climates were examined.	EnergyPlus software was used to simulate the building's energy use, and the parametric analysis tool jEPlus was applied to quantify the impacts of deploying different energy-saving measures on reducing energy use intensity.	Human behaviours, building service system efficiency, and renewable energy had the largest impacts on energy use.
Jang and Kang [63]	Seoul, South Korea	Incorporation of occupants' behaviours into energy simulation of high-rise buildings.	Gaussian Process Classification was applied to modify the random behaviours of occupants related to the probability of energy consumption.	The proposed methodology reduced uncertainties related to occupants' behaviours in building simulations.
Pan et al. [64]	Hong Kong	The challenges related to energy modelling of high-rise buildings in Hong Kong were investigated.	Knowledge barriers to using building energy analysis software were discussed, and a workflow to incorporate energy simulation into the design stage was proposed.	Data transition from BIM software, simulating weather conditions of high-rise, high-density urban contexts, and modelling occupant behaviours were the main challenges in using BIM for high-rise buildings.

3.2. BIM for collaborative design and planning

The increasing complexity of construction projects requires close cooperation of various individuals involved, including the design team, stakeholders, architects, and engineers throughout the entire project lifecycle [12]. Nonetheless, the current mindset in practice presumes that semantic building modelling information is non-existent, and collaborations largely tend to be carried out via traditional ways, e.g. paper printouts [68,69]. Furthermore, el-Diraby et al. [68] mentioned that the scope of collaboration is still limited to single projects and the value of knowledge sharing among various teams is often compromised in ad-hoc decentralised forms of communication. In spite of such reluctance, studies affirmed that the use of BIM can improve collaboration in construction projects by facilitating the exchange of knowledge and information between teams and enabling technological coordination and resource allocation [68,69]. In fact, the use of BIM can be even more instrumental in projects with higher complexities (e.g., high-rise buildings) that require detecting design-related oversights and conflicts at the initial stages of building design.

The results of this review found that 13% of the analysed studies applied BIM to improve collaborative design [70,71] and planning during the design stage of high-rise buildings [72–77] (Table 2). However, in high-rise projects, the use of BIM for communication and collaboration is usually hindered by the extent of model data and the interoperability issue due to differing data format exchanges. In this regard, Sun et al. [70] proposed a BIM-based framework to facilitate collaboration between various teams involved in a high-rise building. The framework aimed to solve four issues attributed to collaborative design in high-rise buildings: multi-speciality collaborative design and management, multi-party collaborative design and management, light-weight interaction of BIM models, and data format exchange between software. Implementing the developed framework was promising in increasing collaborative design in high-rise buildings. Aligned with Sun et al. [70] work, Morales et al. [71] also endeavoured to improve collaborations in high-rise building projects via BIM for processing "requests for information". The results indicated that effective use of BIM could minimise errors during the early stages of building design and reduce their concomitant impacts by facilitating the flow of information.

BIM can also facilitate the coordination of tasks and plan for projects' execution before initiating the construction works. The BIM models offer a holistic understanding of various requirements at different stages of the project lifecycle, enabling construction teams to be better prepared for the execution phase [12]. This is reflected in a number of studies identified by the current paper that used BIM during the design stage for planning purposes such as traffic management [73], scheduling and planning [75,76], and automated compliance checks with codes and regulations [72,74]. For instance, Wang et al. [73] proposed a framework for effective traffic planning by optimising site layouts in high-rise buildings based on integrating BIM and GIS. Choi et al. [72] and Kincelova et al. [74] also developed BIM-based automated code-compliance

Table 2
Summary of studies that used BIM for improving collaborative design and planning in high-rise buildings.

Authors	Location	Areas of focus	Research approach/ applied tools	Findings
Morales et al. [71]	Valparaíso, Chile	Requests for information process during the planning stage of high-rise buildings were analysed.	The potential of using BIM for facilitating a collaborative design was investigated.	The use of BIM facilitated the flow of information between different individuals involved in designing high-rise buildings, thus design-related errors can be detected and rectified prior to initiating the construction stage.
Sun et al. [70]	Chengdu, China	Improving collaborative design.	Four special difficulties in the design of super high-rise buildings were investigated.	A BIM-based framework was proposed to improve the collaborative design in high-rise buildings.
Shi and Wang [77]	Baicheng, China	Improving decision-making processes to select green materials for high-rise buildings.	A green material list allocation technique for high-rise buildings was developed based on BIM technology.	The results indicated that the green material list allocation technique can work better when linked with BIM technology.
Wang et al. [73]	Beijing, China	Optimisation and evaluation of the site layout for effective traffic planning.	PTV VISSIM simulation software was integrated with GIS.	The integrative approach of using BIM and GIS showed promising results in optimising localised traffic design for high-rise buildings by considering the possible impacts of the localised traffic on ambient traffic.
Wang and Liu [75]	Guangzhou, China	Effective scheduling and planning for high-rise buildings.	Seven-dimensional building information model (7D BIM) was proposed.	The application of 7-D can potentially lead to cost and time savings.
Wu et al. [76]	Changsha, China	The accurate estimation of demands for temporary vertical transportation.	A BIM-based framework was proposed, enabling users to accurately estimate demands for temporary vertical transportation.	The results pointed out the capacity of the developed framework for accurate estimation of temporary vertical transportation.
Choi et al. [72]	Seoul, South Korea	Automated regulations compliance checking.	A BIM-based framework was developed to automatically check the compliance of building designs for evacuation with regulations and standards.	The results suggested promising outcomes for reducing errors, time, and inefficient use of human resources.
Kincelova et al. [74]	Montreal, Canada	Automated code-compliance checking for fire safety in high-rise buildings.	A BIM-based framework was developed to automatically check the compliance of architectural building models with fire safety regulations of the National Building Code of Canada.	The results indicated successful implementation of the framework geometrical and non-geometrical requirements of building designs.

checking systems for evacuation and fire safety regulations in high-rise timber buildings, respectively. The automated regulation/code-compliance checking system enabled by the BIM application can lead to minimising errors, increasing the compliance quality of construction works with regulatory frameworks, and reducing inefficient use of human resources via objective verification [15,72].

3.3. BIM for environmental life cycle assessment of high-rise buildings

The life cycle assessment (LCA) is widely acknowledged as a reliable approach to evaluating inputs, outputs, and environmental impacts associated with a given product or service [78–80]. Nonetheless, performing LCA in conventional ways requires collecting bills of quantities related to construction materials which are extremely time-consuming, knowledge-intensive, and subject to errors [78,81]. Therefore, the idea of using BIM to assist the data acquisition process and environmental calculations started gaining momentum [81]. To date, various tools have been developed towards this end. One example is *Tally*, a plug-in for Autodesk Revit software developed to help estimate the environmental impacts of building materials on the basis of LCA methods [82].

This review showed that 12% of the analysed studies used BIM to perform LCA analysis of high-rise buildings (Table 3). For instance, Rivera et al. [83] evaluated the impacts of adopting five passive energy efficiency measures on mitigating life cycle greenhouse gas (GHG) emissions in high-rise residential buildings using the “One Click LCA” plugin for Autodesk Revit. Alotaibi et al. [84] also used the same tool, namely the “One Click LCA” plugin, to evaluate the effectiveness of several de-carbonisation strategies for a high-rise building in India. In addition, studies also proposed BIM-based frameworks to enable performing LCA estimations of high-rise buildings [85–87]. For instance, Xu et al. [87] proposed a framework based on integrating Autodesk Revit with SimaPro to automatically quantify the embodied energy impacts of high-rise prefabricated buildings. The implementation results showed a significant reduction of time for processing the LCA calculations from LCA from 729 min to 62 min while obtaining an 91.5% improvement in efficiency.

Notwithstanding the great potential, the application of BIM for processing life cycle environmental impacts of building design is currently being challenged by several issues [81,90]. In a comprehensive study, Potrč Obrecht et al. [90] categorised these issues into four groups, namely technical, informational, functional requirements, and organisational issues. They discussed their attributed impacts on using BIM for LCA estimations. Among all, there is an issue of interoperability of BIM software and LCA tools, which remains a significant challenge. Furthermore, the LCA is a generic approach used in any sector, whereas BIM is largely utilised in the building sector [81]. This further causes these two paradigms to remain separate in multiple dimensions, e.g., data structure, making the direct data exchange between BIM and LCA challenging. In addition, BIM models developed to represent buildings often contained incomplete data for LCA calculations. For instance, BIM models lack sufficient detailed data on HVAC elements, construction equipment and plants, transportation modes, and transportation distances. Such limitations subsequently lead to the creation of BIM models that lack critical information for LCA estimations, such as inaccurate bills of quantity, thus affecting LCA results. Previous studies [91,92] have highlighted these issues and conclusively recommended that practitioners manually add required data to the BIM databases. This indicates the necessity of developing BIM-based tools for LCA evaluations with databases containing extensive information about buildings’ material properties.

3.4. BIM for the realisation of NZEB

The concept of net-zero energy buildings (NZEBs) has gained popularity over the recent decades due to its capacity to curtail reliance on fossil fuels [93]. The concept of NZEBs resides with counterbalancing the operational buildings’ energy consumption with the amounts of energy that can be generated on/off-site via renewable energy sources within a year [93]. To realise this, the design and construction of buildings should be highly energy efficient to accommodate significant reductions in annual operational energy usage [93,94]. Such buildings thence need to be equipped with renewable energy systems to produce energy [93]. In this regard, optimisation of buildings’ design becomes

Table 3
Summary of studies that used BIM for environmental LCA in high-rise buildings.

Authors	Location	Areas of focus	Research approach/ applied tools	Findings
Alotaibi et al. [84]	New Delhi, India	LCA approach was used to assess de-carbonisation strategies for a high-rise building.	One Click LCA plugin for Autodesk® Revit® was used to analysis the building's LCA performance.	The results suggested that using an appropriate decarbonisation strategy may reduce energy emissions by 70–75%.
Rivera et al. [83]	Toronto, Canada	Reducing life cycle GHG emissions in high-rise residential buildings by using five passive energy efficiency measures.	One Click LCA plugin for Autodesk® Revit® was used to analysis the building's LCA performance.	Using BIM, 16,128 envelope variants, 56 external walls, 12 roofs, six window assemblies, and 4 WWRs were investigated to mitigate the life cycle emissions. Reducing WWR was reported to be the most effective measure to decrease total envelope-related GHG emissions.
Ansah et al. [86]	Hong Kong	Developing BIM-based automated LCA framework for prefabricated high-rise buildings.	Autodesk Revit was used as the BIM tool.	The developed framework was shown to be effective in reducing the energy and environmental impacts associated with building designs.
Cheng et al. [88]	Guangdong, China	Improving the decision-making process by selecting green materials.	Revit and DesignBuilder were used to assess GHG emissions related to building designs.	The results promoted the best practise for sustainable construction.
Gan et al. [85]	Hong Kong	Increasing the sustainable low-carbon design of high-rise buildings.	A BIM-based framework was developed to provide detailed physical and functional characteristics of buildings that could be integrated with various environmental modelling approaches.	The use of the proposed framework can provide decision-making support.
Gan et al. [89]	Hong Kong	Investigated the association between building designs and embodied energy.	ETABS structural analysis software was used to model the high-rise building accurately.	The results showed that steel structures could be the best option to reduce total building embodied energy if 80% of the steel used in buildings was recycled.
Xu et al. [87]	Hong Kong	Automated estimation of embodied energy impacts related to high-rise prefabricated buildings.	A BIM-integrated LCA was developed based on three modules, including i) BIM data preparation (e.g., via Revit), ii) data extraction and integration, and iii) embodied carbon assessment (via SimaPro tool).	The implementation of the proposed framework indicated a significant time reduction in calculating LCA from 729 min to 62 min while obtaining a 91.5% improvement in efficiency.

vital to assure the achievement of NZEBs. This review showed that 10% of studies used BIM to optimise designs of high-rise buildings [95–99], and those used BIM for optimising the integration of photovoltaic (PV) panels with high-rise buildings [100] (Table 4). (See Table 5.)

Giouri et al. [96] developed an integrative approach to minimise the annual energy usage of a high-rise office building, maximising its energy production and enhancing the adaptive thermal comfort of occupants using a multi-objective optimisation approach. EnergyPlus integrated with Rhino and Grasshopper software was used as the energy simulation engine, coupled with the plug-ins Honeybee, Ladybug, and mode-FRONTIER in order to optimise parameters such as WWR, shading area, and PV surface areas. The results showed that the optimised design can reduce the final energy reduction of the building by 33%. Adopting a similar approach, Chen et al. [95] also endeavoured to holistically optimise the architectural design features of a high-rise building and PV utilisation in the building. To this end, NSGA-II and hybrid generalised pattern search particle swarm optimization (HGPSPSO) were applied to optimise parameters attributed to building design such as building orientation, windows, external walls, shading devices and infiltration air change as well as optimising PV panels. The results showed that the use of optimum design configuration can reduce the net building demands by up to 71.36% in the hot summer and warm winter conditions.

3.5. Integration of BIM with smart technologies for designing high-rise buildings

The emergence of BIM has revolutionised the AEC industry, enabling users to develop n-D models enriched with detailed information that are not only object-oriented. Using BIM, practitioners can create reservoir of data suited for building design and performance analysis throughout the entire lifecycle of a project. Nevertheless, BIM still faces a number of challenges that may limit its effective applications in certain domains across the AEC industry. One of these challenges relates to procuring robust real-time visualisation, limiting users' experience for adopting best practices in design, engineering, communication, and coordination at different stages of a project lifecycle [101,102]. In response, the popularity of integrating advanced visualisation technologies such as Augmented Reality (AR) and Virtual Reality (VR) with BIM is on the rise aiming to address the shortcomings of BIM. AR refers to a physical environment in which the elements and objects are augmented with and supported by virtual inputs, while VR is a simulated virtual environment, representing a physical environment [101,102]. The adaption of such technologies facilitates the possibility for users to interact with objects via immersive virtual environments, leading to the improvement of design and decision-making during the initial stages of building design [101].

Table 4
Summary of studies that used BIM for designing high-rise NZEB.

Authors	Location	Areas of focus	Research approach/ applied tools	Findings
Giouri et al. [96]	Athens, Greece	Reaching zero energy by reducing energy demands, increasing energy production and improving thermal comfort.	Multi-objective optimisation approach was adopted using DesignBuilder, and Grasshopper software for developing the model, and using plug-ins Honeybee and Ladybug, coupled with modeFRONTIER for performing optimisation.	The integrative approach towards optimising the building's design reduced the building's annual final energy by 33%.
Alawode and Rajagopalan [98]	Melbourne, Australia	Testing strategies for improving the energy performance of high-rise NZEB in different climatic conditions.	Energy Plus software was used for energy performance analysis.	The findings suggested that proper design and optimisation of the envelope can effectively improve a building's energy performance.
Hoseinzadeh et al. [97]	Tehran, Iran	The optimised design of a high-rise office building equipped with photovoltaic panels in the building (BIPV).	Honeybee and EnergyPlus plugins of the Rhinoceros software were used.	The results showed that the amount of electricity supplied by BIPV could reduce GHG by 87 tons of CO2 per year.
Vahdatikhaki et al. [100]	Montreal, Canada	Developed a BIM-based generative design of PV modules for high-rise buildings.	The presented framework enables users to design PV module layouts on the exteriors of tall buildings.	The proposed framework showed promising results in generating favourable design solutions compared to baseline scenarios.
Wu et al. [99]	Five cities in China	Finding the optimal energy-saving design solution for a high-rise residential building.	A parametric design approach was adopted using the Grasshopper platform and the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) to realise the lowest total air-conditioning and heating load, the highest PV energy generation, and the lowest investment cost.	The results suggested feasibility and technical routes for achieving NZEB in different climate zones in China.
Chen et al. [95]	Hong Kong	Investigated the impacts of passive architectural design strategies on PV and renewable energy production.	Applied optimisation approach, namely NSGA-II and HGPSPSO and sensitivity analysis.	The findings showed that the use of optimum design configuration could reduce the net building demands in the hot summer and warm winter conditions.

The results of this review identified a limited number of studies that used visualisation technologies for designing high-rise buildings [102–104]. For instance, Gan et al. [102] presented a framework based on the integration of BIM and VR to analyse the aerodynamic design and wind comfort for high-rise modular buildings in Singapore. The framework consisted of four primary components including the combination of OpenStreetMap and Dynamo used to achieve rapid urban modelling of modular buildings. The second phase involved employing CFD to simulate the outdoor wind environment surrounding modular buildings. In the third phase, CFD-computed data was integrated with VR applications to develop an immersive virtual environment for designers enabling them to analyse various design alternates for the wind environment. Finally, the visual experience of non-professional users was used to enhance the building's ventilation and support the process of decision-making at the initial stage of building design. The implementation results showed that the use of VR for visualisation of CFD simulations provided designers with great details regarding various spatial dimensions, which can potentially lead to optimising architectural designs. There were also studies that deployed other types of technologies to aid with using BIM for designing high-rise buildings such as integrating BIM with BIM and LiDAR to augment multi-source data with architectural knowledge [105], and combining BIM software tools with wireless automatic monitoring systems for identifying low-carbon design alternatives [106]. Donath and Lobos [107] also developed a new BIM-based tool that enabled designers to generate various design alternatives for building envelopes of high-rise structures while reducing computation time.

The findings of this review pointed out that the coalescence of BIM with advanced visualisation technologies (e.g., VR/AR) can be a promising solution for optimising practices during the design stage of high-rise buildings. Nonetheless, the use of AR and VR technologies in the AEC industry is still in its infancy. One of the main challenges attributes to the interoperability and exchange of data between AR and VR technologies and BIM software applications that are being currently used in the AEC industry. For instance, the data generated by the available AR and VR technologies are incompatible with the standard data formats being commonly used in the industry, e.g., Industry Foundation Classes. This incompatibility makes the process of synchronising and integrating data between AR and VR software tools and AEC software packages very difficult. To date, a number of commercial solutions have been developed to provide a degree of automated synchronisation between BIM to VR platforms such as Enscape, InsiteVR, or IrisVR [108]. The use of these mediums only enables converting BIM models into visualised VR environments [108]. However, it is still impossible to establish a bi-directional synchronisation between BIM and VR environments. This mainly relates to the difference between data schemas employed for developing BIM models in the AEC industry and VR models, as well as the absence of compatible databases for federated models [108]. This highlights an area for improvement by future studies.

3.6. BIM for cost design analysis of high-rise buildings

The benefits of using BIM for cost analysis and increasing the return on investment (ROI) in construction projects by preventing schedule delays are well documented [12]. The application of BIM at the early stage of building design increases the viability of a building project to be completed within the determined budget. This is often implemented by using BIM for detecting clashes in-between technical plans or design errors in the pre-construction phase to minimise reworks during construction [12]. However, high-rise buildings are more susceptible to experiencing issues related to design errors due to the involvement of individuals from various domains of expertise, such as architecture, structural engineers, mechanical, electrical, and plumbing. This review revealed that only 5% of studies employed BIM for cost analysis of high-rise buildings at the design stage [109–111]. For instance, Ham et al. [110] used BIM for analysing the cost of potential economic losses attributed to design errors in high-rise buildings. To this end, the design errors were first classified into three groups, namely simple design, rework-related and delay-related errors, thence BIM was used to quantitatively examine the effects of these errors. The results showed that the total cost of design errors causing schedule delays was 194.69% higher compared to simple design errors.

BIM can also be instrumental in translating the benefits of improving buildings' energy efficiency into monetary values so that stakeholders can better understand and decide about selecting various building components, systems, and services during the design stage. For instance, Cho et al. [109] used an integrated approach for analysing the exterior shading design of a high-rise building in Seoul, South Korea. The

Table 5
Summary of studies integrated smart technologies with BIM for designing high-rise buildings.

Authors	Location	Areas of focus	Research approach/ applied tools	Findings
Gan et al. [102]	Singapore	Analysing aerodynamic design and wind comfort levels for high-rise modular buildings.	Developing a framework based on integrating BIM and VR to analyse the wind environment of design alternates.	The architectural building designs were optimised via visualising CFD simulations in VR.
Zhao et al. [104]	Beijing, China	Structural design of a high-rise building with the aid of using BIM combined with AR and Mixed Reality (MR).	Modelling BIM tools (e.g., Rhino, Revit, Sketchup) were used for simulating geometrical attributes of the buildings, combined with simulation tools (e.g., TRNSYS, EnergyPlus, and Radiance), format-conversion tools, and AR/ MR apps.	The implementation results indicated promising outcomes for designing high-rise buildings via AR/MR.
Huang [106]	Nanchang, China	Designing low-carbon emission buildings.	A framework was developed to integrate BIM (e.g., Revit and Ecotect) with the wireless automatic monitoring system.	The implementation results showed successful framework contributions for identifying low-carbon design alternatives.
Yabuki et al. [103]	Osaka, Japan	Assessment of buildings' heights with respect to the surrounding landscape.	A method was proposed using BIM and VR to enable evaluating the height of high-rise buildings in accordance with the municipality requirements.	The proposed method was tested, and the results indicated its effective implementation.
Chen et al. [105]	Hong Kong	Automatic reconstruction of BIMs in high-density urban areas.	A method based on BIM and LiDAR was developed allowing users to automatically reconstruct BIMs of high-rise buildings from topographic maps.	The method was tested by retrieving 1361 buildings located in a four-square-kilometre area of Hong Kong, showing the capacity of the proposed model for decreasing computation time and improving the level of automation.
Donath and Lobos [107]	Weimar, Germany	Improving the design of envelopes for high-rise residential buildings.	A BIM-based tool was developed enabling users to generate various design alternatives for building envelopes.	The implementation results suggested that the use of tools can contribute to providing viable envelope design solutions for high-rise buildings, and minimising computation time.

analyses were conducted using DOE-2.1E simulation software to investigate the cooling energy-saving potential of using shading devices, along with evaluating the cost benefits related to integrating shading devices. The results showed that improvements in energy savings and operational costs could be achieved by integrating exterior shading devices. Gan et al. [111] proposed a BIM-based optimisation approach for designing cost-optimal and low-carbon high-rise concrete buildings. The optimisation was carried out using an evolutionary optimisation technique, i.e., genetic algorithm, and led to reducing the building plan's carbon emissions and material costs by 18–24%.

3.7. BIM for the structural design of high-rise buildings

The key to effective implementation of building design resides in establishing a successful collaboration between all the individuals involved in a project. The ever-increasing complexity of modern architecture further underlines the necessity of collaboration between architects and engineers [112]. However, in conventional practice, architects and engineers often operate in isolation, with limited synergies between them during the early stages of building design [112]. This can lead to producing architectural plans by architects that are realistically infeasible to be superimposed with the structural plans generated by structural engineers, e.g., the effects of architectural design on structural performance are overlooked [12,112]. In this regard, the application of BIM can ease the situation by bridging the gap between architects and engineers, such as structural engineers, and help optimise building designs. However, the findings of this review indicated that only 7% of the analysed studies used BIM for the structural design of high-rise buildings [112–115]. For instance, Hamidavi et al. [112] developed a BIM-based framework to integrate architectural models with structural ones for high-rise buildings. The proposed framework enabled the automatic generation of structural models and updated them following the inputs extracted from architectural models. Applying this BIM-based model can assist engineers in devising building designs that fulfil the required criteria.

4. Discussions

BIM is currently being applied across various disciplines in the AEC industry. However, scant attention has been given to using BIM for the assessment of high-rise buildings' performance at the early stage of building design. Correspondingly, this study conducted a systematic literature review in order to provide a status quo understanding of the current BIM applications in high-rise buildings. A summary of the findings is illustrated in Fig. 6. As shown, seven domains of BIM employment have been identified, including i) the use of BIM for and optimising buildings' energy efficiency, ii) facilitating collaborative design and planning, iii) performing environmental life-cycle assessment, iv) designing NZEBs, v) integrating BIM with smart technologies, vi) cost analysis, and vii) structural design of high-rise buildings. The analysis showed that BIM has been used by the majority of studies for enhancing the energy efficiency performance of cases and minimising

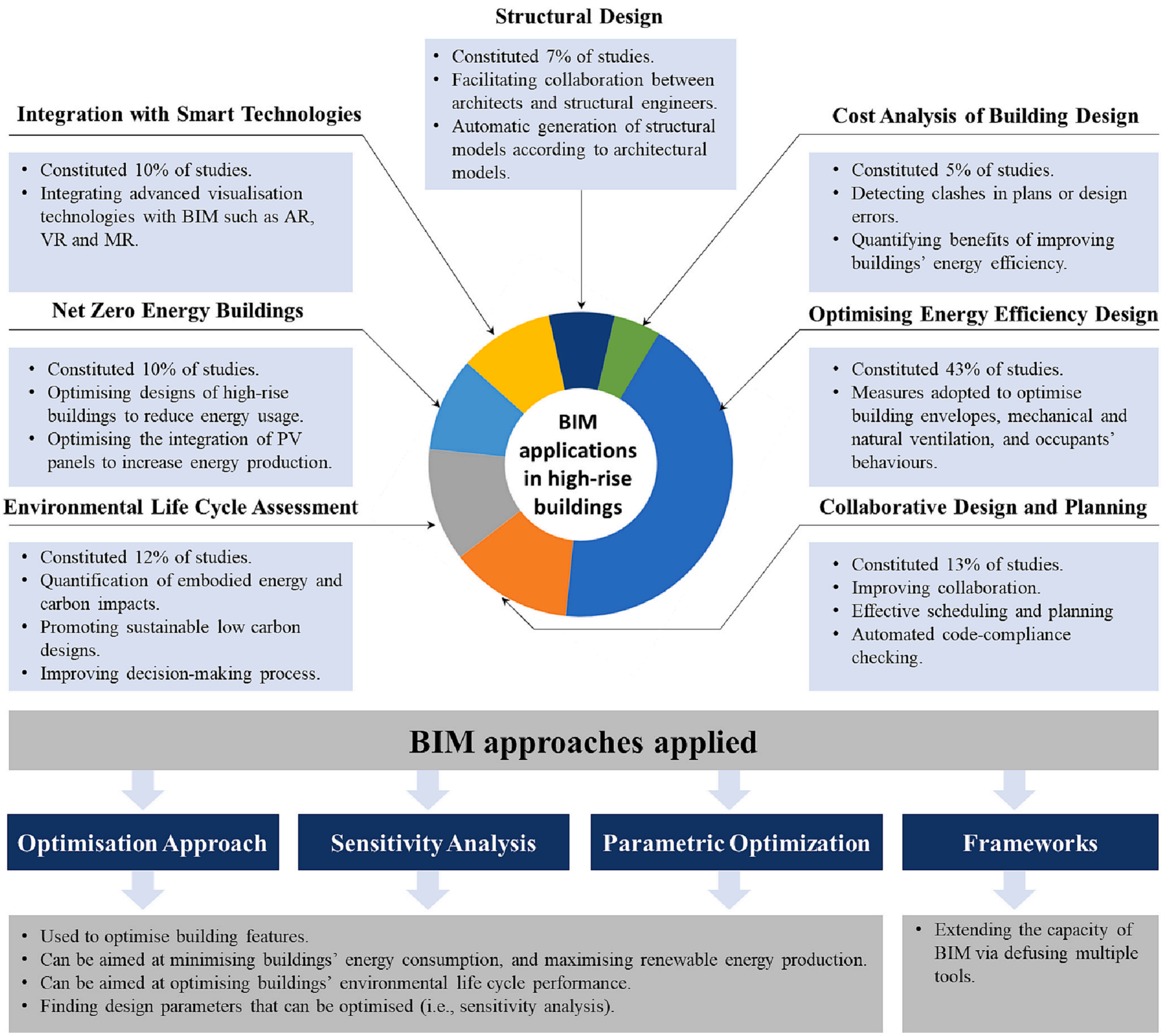

Fig. 6. Summary of 60 reviewed studies.

their attributed carbon emissions. Comparatively, less attention is given to using BIM for cost analysis and structural design of these buildings.

4.1. Approaches of reviewed studies for using BIM

The approaches adopted by the reviewed studies for implementing BIM at the design stage of high-rise buildings can be generally categorised into four groups i) optimisation approach [57,95,96,99], ii) sensitivity analysis [44,45,52,58,62,63], iii) parametric optimization approach [39,41–43,46,48–51,53], and iv) devising frameworks. The first three approaches have been commonly used to improve cases' energy efficiency performance and increase renewable energy production. The fourth approach has been employed by the reviewed studies aiming to extend the capacity of BIM by diffusing several software tools.

This review found studies that used an optimisation approach for increasing the energy efficiency performance of high-rise buildings [57,95] and achieving NZEBs [96,99]. The optimisation approach is a process in which the most optimum solutions for a given design problem are identified from a defined set of alternatives [116]. The selection of the optima is often implemented based on a set of performance criteria expressed as mathematical functions, also known as objectives [116]. In optimisation approach, the objective functions are defined to become either maximised or minimised in order to identify the best possible solutions. For instance, Gan et al. [57] used a simulation-based optimisation method to identify the most energy-efficient layout plan configurations for a 40-storey residential building in Hong Kong. To this end, an evolutionary genetic algorithm was developed to find design solutions leading to maximisation of building energy efficiency. The results showed that the use of optimisation approach could potentially minimise 30–40% of the total energy consumption related to air-conditioning and lighting systems used in the building. In another study, Wu et al. [99] investigated possibilities for achieving NZEBs by optimising building design and the technologies used in the building for producing energy via renewables. To do this, an optimisation approach was used based on employing the NSGA-II algorithm in the Grasshopper platform in order to minimise energy consumption associated with the air-conditioning while finding design scenarios to maximise energy production. The outcomes of the study offered a theoretical basis, along with introducing a methodological approach for realising NZEBs in different regions of China.

The second approach used commonly by the reviewed studies was the sensitivity analysis. Using this method, the uncertainties in the output of simulation models can be allocated to their corresponding uncertainties in the input [117,118]. This method has been widely applied in simulation studies due to its capacity for identifying parameters with the highest impacts on the outputs of a model [117,118]. In general, sensitivity analysis can be implemented via two methods, namely local sensitivity analysis and global sensitivity analysis [117,118]. The former aims at determining the impacts of uncertain inputs around a certain point (or base case), whereas the latter focuses on examining the influence of uncertainties attributed to inputs over the entire input space. Hence it is deemed to be more reliable [117,118]. This review identified several studies that utilised the sensitivity analysis approach for optimising buildings' energy efficiency performance [44,45,52,58,62,63]. For instance, Yu et al. [44] conducted a sensitivity analysis to evaluate the impacts of different envelope design parameters on the energy performance of high-rise buildings in four Chinese cities with hot summer and cold winter zones. The sensitivity analysis showed that shading coefficients and WWR were the most critical factors impacting buildings' energy performance during the cooling season, while wall heat-transfer coefficients and shape coefficients were the two most influential parameters affecting the energy performance of buildings in hot seasons. Similarly, Moujahed et al. [58] applied a global sensitivity analysis method to determine the most influential design parameters affecting the energy usage of high-rise buildings in Lusail City, Qatar. The results showed that the cooling setpoint, the outdoor air requirements, the equipment power density, and the lighting power density were the most important parameters contributing to buildings' energy consumption.

Parametric optimisation was another approach used commonly by the reviewed studies for evaluating and optimising buildings' designs [39,41–43,46,48–51,53]. This term, which originated from mathematical science, refers to amending certain design parameters to manipulate the modelling results [119]. The parameters are fundamental elements of a system (e.g., orientation or building's location) that are vital in identifying a system or assessing the performance of a given system, its status, or operating condition. In the building context, the correlations between building design objects are defined as parameters so that their relationships can be reformulated [119]. The application of parametric optimisation approach enables generating numerous variations of a given building model, thus enabling the exploration of suitable ways for assessing various alternatives at the initial stage of building design. Unlike optimisation which establishes a blank slate for users to investigate the design space and identify optimal design solutions, parametric optimisation requires developing an initial design of the building model for further examination. Table 6 shows a number of software tools used by the reviewed studies for evaluating and optimising the performance of high-rise buildings. For instance, Saroglou et al. [51] used Google SketchUp to develop the building's 3D geometry, thence employed the EnergyPlus plugin to analyse the energy efficiency performance of different double-skin curtain wall systems installed in high-rise buildings. Studies also employed DesignBuilder software to develop the initial building designs for parametric analysis, and used the EnergyPlus simulation engine to analyse energy performance [43,48,54] and CFD analysis [60].

Table 6
Parametric tools applied for performance analysis of high-rise buildings.

Parametric analysis	Software applied
Study on optimum energy-efficient double-skin curtain wall design for high-rise buildings [51].	EnergyPlus plugin of Google SketchUp
Energy performance analysis of high-rise buildings [46].	ArchiCAD software
Parametric energy performance analysis [43,48,54].	EnergyPlus simulation engine was used as a plug-in for DesignBuilder
CFD analysis [60].	EnergyPlus simulation engine was used as a plug-in for DesignBuilder
Evaluating the thermal performance of a DSF system used in a high-rise apartment building [50].	Air Flow Network model was developed via EnergyPlus software
Parametric energy analysis [42].	Autodesk Ecotect
Optimising facade design for naturally ventilated residential buildings [41].	ESP-r and FLUENT software tools were used
Analysis of windows' energy performance in high-rise residential buildings [39].	HTB2 Software
Analysis of energy-efficient envelope designs for high-rise apartments [40].	TRNSYS Software
Parametric energy analysis of high-rise buildings [49] [98].	EnergyPlus simulation software

Lastly, several studies have attempted to extend the capacity of BIM by fusing multiple software tools together for various purposes. This is often done by developing frameworks that introduce certain working principles to regulate the operations of these tools in conjunction with each other. This approach is manifested in most of the BIM applications identified by this review, such as the optimisation of high-rise buildings' energy efficiency performance [47,56], collaborative design and planning [70,72,74,76], environmental life cycle assessment of high-rise buildings [85,86], designing NZEBs [100], and integrating BIM with other technologies such as VR, AR and wireless automatic monitoring system [102,106].

4.2. Challenges and future directions

The findings of this review underline the great potential of BIM for supporting decision-making at the early stage of high-rise building designs. Nonetheless, the widespread implementation of BIM still faces several challenges and uncertainties that future studies can address.

(i) *Simplifications in modelling and performing analysis*. One of the primary purposes of using BIM is to analyse the environmental impacts or energy performance of building designs, as reflected in the findings of this study. The common approach in modelling high-rise buildings is to simplify building designs [64] by i) modelling one typical storey, ii) modelling many floors representing the top, middle and ground floors, and iii) modelling a flat representing all the storeys. In addition, modelling the interactions and interdependency between building fabric, building services and renewable energy production technologies is more challenging in high-rise buildings. Hence, the common approach is to carry out modelling buildings' physical enclosures and building systems separately, which can be time-consuming and prone to errors.

Another simplification relates to performing high-rise buildings' performance analysis in which the effects of surrounding environments on the buildings' operations are often excluded from the analyses. This contrasts with the fact that weather conditions around tall buildings can be highly complex, varying in wind velocity, temperature, and atmospheric pressure due to the higher altitude [64]. These simplifications are often justified based on minimising computation time. Nevertheless, considering such simplifications can impact the quality of simulation results and affect decision-making. Therefore, this study proposes that a set of rules governing the simplification of the modelling process should be developed to standardise the modelling process, aiming to assure the soundness and accuracy of modelling results.

(ii) *Incorporating occupants' behaviours*. The proper incorporation of occupants' behaviours into high-rise buildings' performance analysis, e.g., energy analysis, is another daunting challenge related to the use of BIM. The estimation of buildings' energy performance carried out by the majority of available software tools is based on evaluating the thermal performance of building envelopes and the energy that would be expected to be used by occupants via their interactions with building systems and appliances. Nevertheless, the accurate estimation of energy usage caused by occupancy remains a challenge for BIM users. This issue stems from multiple sources. First, it is difficult to accurately predict the occupants' choice and possession of electrical appliances during the occupancy stage. Many factors, such as the financial ability of occupants, cultural backgrounds, or social norms, usually influence such decisions. Hence, certain values are often assumed for energy use per building area during the simulation, which can potentially undermine the accuracy of results [64,78]. Second, the accurate prediction of operating time for appliances and building services deployed in buildings is also very challenging and always subjects to uncertainty. As an illustration, it is hard to foresee how occupants would utilise natural ventilation in combination with mechanical air conditioning systems. In using BIM software tools, the determination of use patterns for natural and mechanical air conditioning systems is largely based on defining setpoints for cooling and heating and scheduling the operation of HVAC system [64]. Since there is a great diversity in the living habits of occupants in high-rise buildings, the common trend is to assume certain setpoints for cooling and heating. This, in turn, leads to affecting the accuracy of simulation results.

A viable solution to this challenge is to conduct comprehensive surveys to understand the tendency to adjust cooling and heating setpoints in different regions. A similar attempt undertaken by the Census and Statistics Department of Hong Kong, provided the number of hours people spent sleeping and working via surveying 6100 households [120]. The result of such surveys can increase the reliability of BIM results and improve confidence in using this approach to support decision-making at the initial stage of high-rise building designs.

(iii) *Interoperability*. The issue of interoperability is still challenging the employment of BIM across the AEC industry. This review also highlighted this challenge where BIM was used for communication and collaboration, performing LCA analysis, and integrated with advanced visualisation technologies such as AR and VR. In facilitating interoperability among BIM applications, extraction and exchange of data are the two key processes that need to be managed properly. Studies endeavoured to address these aspects of interoperability. For instance, Ladenhauf et al. [121] proposed an algorithm that would enable data to be automatically extracted from BIM models. Similarly, Hamidavi et al. [112] proposed a framework for the automatic extraction of structural data from architectural BIM models. Attempts have also been undertaken to improve the process of exchanging data between BIM applications. Utkucu and Sözer [122] developed a framework enabling the exchange of data between different BIM tools when evaluating buildings' energy performance and indoor comfort. Nonetheless, this issue still remains for a large number of BIM applications such as semantic interoperability between BIM-based energy simulation and visualisation software or LCA software applications.

To overcome this challenge, open-source standards should be developed to standardise generating data that can be exchanged with BIM platforms across different disciplines of the AEC industry. This should be coupled with extending the capabilities of current BIM standards for exchanging data with VR and AR tools seamlessly.

(iv) *Integrative optimisation*. To date, multiple simulation software packages can carry out energy analysis of building cases. For example, the US Department of Energy has listed over four hundred software tools enabling users to conduct building energy analysis, among which many can simulate whole building energy [123]. Nevertheless, fewer developments have been achieved so far when performing an integrative optimisation (single and multi-objectives) analysis of building design. Currently, the common approach for optimisation is to develop a building model using energy simulation tools, e.g., TRNSYS, and simulate its performance, then optimise the obtained results in an external environment, e.g., MATLAB using optimiser applications. However, this process is complicated and requires running simulations and computer programming expertise. Hence may be unfriendly for architects to use at the early stages of high-rise building design. DesignBuilder is one of the few tools currently available that allows performing single and multi-objective optimisation within the environment/platform where 3D models are developed. Nonetheless, this simulation application only utilises the NSGA2 algorithm [124], thus users cannot modify, input, or have the choice to select a different optimisation algorithm. This underlines the necessity of developing user-friendly software tools that allow architects to conduct integrative optimisation at the early stages of building design.

5. Conclusions

The literature connected to the employment of BIM is enriched by studies that have explored various aspects of implementing this approach. Nonetheless, little is known about the applications of BIM in high-rise buildings and its contributions at the early stage of building design. High-rise buildings are more complicated compared to low-and-mid-size buildings. These buildings are also more energy-consuming with greater environmental impacts; thus, it is critical to adapt the best practices at the early stage of building design. To be manageable, the scope of this review paper has been limited to only studies that applied BIM during the design stage of project lifecycle. The search was conducted through scholarly databases, and 60 studies were selected for detailed examinations. The findings can be summarised as follows:

- Using keyword co-occurrence analysis carried out via VOSviewer software, seven themes for BIM applications in high-rise buildings were identified, including i) optimisation of building energy efficiency design; ii) application of BIM for collaborative design and planning; iii) life-cycle assessment (LCA); iv) realisation of net-zero energy buildings (NZEB); v) integration of BIM with smart technologies for designing high-rise buildings; vi) cost analysis, and vii) the use of BIM for the structural design of high-rise buildings.
- The analysis of 60 selected studies showed that 45% of studies were conducted on cases in China and Hong Kong, followed by South Korea and Canada, with six and four studies that applied BIM for investigating high-rises at the early stage of the project lifecycle, respectively. Further, the analysis revealed that most of the analysed studies were done in Cwa (26%) (humid subtropical climate), Cfa (21%) (warm temperate climate), and Dwa (12%) (humid continental climate). These findings indicate that BIM has a great potential for further research in regions where high-rise buildings are already a common norm in construction (e.g., Thailand, the UK, or Australia) (See Fig. 1).
- The results showed that most identified studies (i.e., 26 studies) used BIM to improve the energy efficiency of high-rise building designs by optimising different features of building envelopes. The measures used by the reviewed studies for increasing the energy efficiency of high-rise designs have been categorised into three groups: building envelope, mechanical ventilation, and occupants' behaviours. The strategies used by the analysed studies for improving the energy performance of building envelopes were further categorised into two major groups, including designed-related and construction-related. The designed-related group encapsulated strategies targeting multiple design features to improve the overall energy performance of buildings thereby, namely i) window features (e.g., U-values, glazing types, orientation, and window-to-wall ratio), ii) integrating shading systems, iii) building geometry and shape co-efficient, iv) colours of

external surfaces, and v) considering climate conditions. The construction-related strategies used by the analysed studies targeted the improvement of i) the use of double skin façade and ii) thermal insulation for exterior walls.
- The analysis also showed that BIM was used for collaborative design and planning, performing LCA analysis and designing NZEBs in 13%, 12%, and 10% of the reviewed studies. In high-rise projects, the use of BIM for communication and collaboration is usually hindered by the extent of model data and the interoperability issue due to differing data format exchanges. Nevertheless, the findings showed that BIM models could offer a holistic understanding of various requirements at the initial building design stage, enabling construction teams to be better prepared for the execution phase. Additionally, one of the promising findings of this review was the coalescence of BIM with advanced visualisation technologies (e.g., VR/AR) for optimising the design of high-rise buildings and decision-making processes. Integrating such technologies with BIM can facilitate the possibility for users to interact with objects via immersive virtual environments, improving design and supporting decision-making during the initial stages of building design.
- This study has also identified four major challenges requiring to be addressed by future research aiming to streamline the application of BIM in high-rise buildings, including i) the simplifications often considered in modelling high-rise buildings and carrying out performance analysis, ii) incorporating occupants' behaviours into energy simulation software, iii) the issue of interoperability, and iv) the lack of available user-friendly tools for performing integrative design optimisation.

Declaration of Competing Interest

The authors declare that they have no conflicting interests that may influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

[1] IEA, Buildings, IEA, 2022. Available from: https://www.iea.org/reports/buildings. Accessed: [26/10/2022].
[2] United Nations, Peace, Dignity and Equality on a Healthy Planet, Available from, https://www.un.org/en/global-issues/population, 2022. Accessed: [26/10/2022]..
[3] CTBUH, Available from: https://www.ctbuh.org/, 2022. Accessed: [26/10/2022].
[4] S. Cai, Z. Ma, M.J. Skibniewski, S. Bao, Construction automation and robotics for high-rise buildings over the past decades: a comprehensive review, Adv. Eng. Inform. 42 (2019), 100989, https://doi.org/10.1016/j.aei.2019.100989.
[5] F. Mostafavi, M. Tahsildoost, Z. Zomorodian, Energy efficiency and carbon emission in high-rise buildings: a review (2005-2020), Build. Environ. 206 (2021), 108329, https://doi.org/10.1016/j.buildenv.2021.108329.
[7] Y. Wang, D. Mauree, Q. Sun, H. Lin, J.L. Scartezzini, R. Wennersten, A review of approaches to low-carbon transition of high-rise residential buildings in China, Renew. Sust. Energ. Rev. 131 (2020), 109990, https://doi.org/10.1016/j.rser.2020.109990.
[8] IEA, High-Rise Refurbishment, Available from, https://www.iea.org/reports/high-rise-refurbishment, 2006. Accessed: [9/12/2022].
[9] CTBUH, Countries by the Number of High-Rise Buildings, Available from, https://www.skyscrapercenter.com/countries?list=buildings-150, 2022. Accessed: [9/12/2022].
[10] P. Steadman, High-rise buildings much more energy intensive than low-rise, Phys. Oceanogr. (2017). Available from, https://phys.org/news/2017-06-high-rise-energy-intensive-low-rise.html. Accessed: [9/12/2022].
[11] D. Godoy-Shimizu, P. Steadman, I. Hamilton, M. Donn, S. Evans, G. Moreno, H. Shayesteh, Energy use and height in office buildings, Build. Res. Inf. 46 (8) (2018) 845–863, https://doi.org/10.1080/09613218.2018.1479927.
[12] A. Ghaffarianhoseini, J. Tookey, A. Ghaffarianhoseini, N. Naismith, S. Azhar, O. Efimova, K. Raahemifar, Building information modelling (BIM) uptake: clear benefits, understanding its implementation, risks and challenges, Renew. Sust. Energ. Rev. 75 (2017) 1046–1053, https://doi.org/10.1016/j.rser.2016.11.083.
[13] X. Zhao, A scientometric review of global BIM research: analysis and visualization, Autom. Constr. 80 (2017) 37–47, https://doi.org/10.1016/j.autcon.2017.04.002.
[14] H. Omrany, A. Ghaffarianhoseini, A. Ghaffarianhoseini, D.J. Clements-Croome, The uptake of City information modelling (CIM): a comprehensive review of current implementations, challenges and future outlook, Smart Sustain. Built Environ. (2022), https://doi.org/10.1108/SASBE-06-2022-0116.
[15] C.M. Eastman, C. Eastman, P. Teicholz, R. Sacks, K. Liston, BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors, John Wiley & Sons, 2011.
[16] NBIMS-US, National BIM Standard-United States® Version 3, Available from, http://mddb.apec.org/Documents/2013/SCSC/WKSP5/13_scsc_wksp5_007.pdf, 2013. Accessed: [9/12/2022].
[17] D.K. Smith, M. Tardif, Building Information Modeling: A Strategic Implementation Guide for Architects, Engineers, Constructors, and Real Estate Asset Managers, John Wiley & Sons, 2009.
[18] E. Sackey, M. Tuuli, A. Dainty, Sociotechnical systems approach to BIM implementation in a multidisciplinary construction context, J. Manag. Eng. 31 (1) (2015) A4014005, https://doi.org/10.1061/(ASCE)ME.1943-5479.0000303.
[19] T.A. Nguyen, S.T. Do, P.T. Nguyen, Application of building information modeling (BIM) in volume management of construction projects, JARDCS 12 (2) (2020) 1845–1852, https://doi.org/10.5373/JARDCS/V12I2/S20201228.
[20] Y. Yang, M. Pan, W. Pan, Z. Zhang, Sources of uncertainties in offsite logistics of modular construction for high-rise building projects, J. Manag. Eng. 37 (3) (2021) 04021011, https://doi.org/10.1061/(ASCE)ME.1943-5479.0000905.
[21] Q. Chen, B.T. Adey, C.T. Haas, D.M. Hall, Exploiting digitalization for the coordination of required changes to improve engineer-to-order materials flow management, Constr. Innov. 22 (1) (2022) 76–100, https://doi.org/10.1108/CI-03-2020-0039.
[22] F. Morales, R.F. Herrera, F.M.L. Rivera, E. Atencio, M. Nuñez, Potential application of BIM in RFI in building projects, Buildings 12 (2) (2022) 145, https://doi.org/10.3390/buildings12020145.
[23] J. Xue, X. Hou, High-rise building construction Progress measurement from top view based on component detection, Buildings 12 (2) (2022) 106, https://doi.org/10.3390/buildings12020106.
[24] T. Liu, B. Yang, Q. Zhang, Health monitoring system developed for Tianjin 117 high-rise building, J. Aerosp. Eng. 30 (2) (2017) B4016004, https://doi.org/10.1061/(ASCE)AS.1943-5525.0000602.
[25] B. Atazadeh, M. Kalantari, A. Rajabifard, S. Ho, T. Ngo, Building information modelling for high-rise land administration, Trans. GIS 21 (1) (2017) 91–113, https://doi.org/10.1111/tgis.12199.
[26] B. Atazadeh, H. Olfat, A. Rajabifard, M. Kalantari, D. Shojaei, A.M. Marjani, Linking land administration domain model and BIM environment for 3D digital cadastre in multi-storey buildings, Land Use Policy 104 (2021), 105367, https://doi.org/10.1016/j.landusepol.2021.105367.
[27] B. Manzoor, I. Othman, J.C. Pomares, H.Y. Chong, A research framework of mitigating construction accidents in high-rise building projects via integrating building information modeling with emerging digital technologies, Appl. Sci. 11 (18) (2021) 8359, https://doi.org/10.3390/app11188359.
[28] N. Lotfi, B. Behnam, F. Peyman, A BIM-based framework for evacuation assessment of high-rise buildings under post-earthquake fires, J. Build. Eng. 43 (2021), 102559, https://doi.org/10.1016/j.jobe.2021.102559.
[29] H. Chen, L. Hou, G.K. Zhang, S. Moon, Development of BIM, IoT and AR/VR technologies for fire safety and upskilling, Autom. Constr. 125 (2021), 103631, https://doi.org/10.1016/j.autcon.2021.103631.
[30] M. Al Hattab, E. Zankoul, M. Barakat, F. Hamzeh, Crane overlap and operational flexibility: balancing utilization, duration, and safety, Constr. Innov. 18 (1) (2018) 43–63, https://doi.org/10.1108/CI-11-2016-0062.
[31] J. Choi, J. Choi, I. Kim, Development of BIM-based evacuation regulation checking system for high-rise and complex buildings, Autom. Constr. 46 (2014) 38–49, https://doi.org/10.1016/j.autcon.2013.12.005.
[32] J. Melzner, S. Zhang, J. Teizer, H.J. Bargstädt, A case study on automated safety compliance checking to assist fall protection design and planning in building information models, Constr. Manag. Econ. 31 (6) (2013) 661–674, https://doi.org/10.1080/01446193.2013.780662.
[33] N.I. Wardahni, L.S. Riantini, Y. Latief, R.A. Machfudiyanto, Identification of e-maintenance elements and indicators that affect maintenance performance of high rise building: A literature review, in: 3rd Tarumanagara International Conference of the Applications of Technology and Engineering, TICATE 2020, IOP Publishing Ltd., 2020, https://doi.org/10.1088/1757-899X/1007/1/012021.
[34] S. Mirrahimi, M.F. Mohamed, L.C. Haw, N.L.N. Ibrahim, W.F.M. Yusoff, A. Aflaki, The effect of building envelope on the thermal comfort and energy saving for high-rise buildings in hot–humid climate, Renew. Sust. Energ. Rev. 53 (2016) 1508–1519, https://doi.org/10.1016/j.rser.2015.09.055.
[35] VOSviewer, Available from: https://www.vosviewer.com/, 2022. Accessed: [30/11/2022].
[36] H. Omrany, A. Ghaffarianhoseini, A. Ghaffarianhoseini, K. Raahemifar, J. Tookey, Application of passive wall systems for improving the energy efficiency in buildings: a comprehensive review, Renew. Sust. Energ. Rev. 62 (2016) 1252–1269, https://doi.org/10.1016/j.rser.2016.04.010.
[37] H. Omrany, A. Marsono, Optimization of building energy performance through passive design strategies, Br. J. Appl. Sci. Technol. 13 (6) (2016) 1–16, https://doi.org/10.9734/BJAST/2016/23116.

[38] F. Kheiri, A review on optimization methods applied in energy-efficient building geometry and envelope design, Renew. Sust. Energ. Rev. 92 (2018) 897–920, https://doi.org/10.1016/j.rser.2018.04.080.
[39] M. Bojic, F. Yik, P. Sat, Energy performance of windows in high-rise residential buildings in Hong Kong, Energy Build. 34 (2002) 71–82, https://doi.org/10.1016/S0378-7788(01)00079-2.
[40] C.K. Cheung, R.J. Fuller, M.B. Luther, Energy-efficient envelope design for high-rise apartments, Energy Build. 37 (2005) 37–48, https://doi.org/10.1016/j.enbuild.2004.05.002.
[41] L. Wang, H.W. Nyuk, S. Li, Facade design optimization for naturally ventilated residential buildings in Singapore, Energy Build. 39 (2007) 954–961, https://doi.org/10.1016/j.enbuild.2006.10.011.
[42] N. Al-Tamimi, S.F.S. Fadzil, Energy-efficient envelope design for high-rise residential buildings in Malaysia, Archit. Sci. Rev. 55 (2012) 119–127, https://doi.org/10.1080/00038628.2012.667938.
[43] Y. Yaşar, S.M. Kalfa, The effects of window alternatives on energy efficiency and building economy in high-rise residential buildings in moderate to humid climates, Energy Convers. Manag. 64 (2012) 170–181, https://doi.org/10.1016/j.enconman.2012.05.023.
[44] J. Yu, L. Tian, C. Yang, X. Xu, J. Wang, Sensitivity analysis of energy performance for high-rise residential envelope in hot summer and cold winter zone of China, Energy Build. 64 (2013) 264–274, https://doi.org/10.1016/j.enbuild.2013.05.018.
[45] B. Raji, M.J. Tenpierik, A. Van Den Dobbelsteen, An assessment of energy-saving solutions for the envelope design of high-rise buildings in temperate climates: a case study in the Netherlands, Energy Build. 124 (2016) 210–221, https://doi.org/10.1016/j.enbuild.2015.10.049.
[46] S.B.M. Ali, A. Mehdipoor, N. Samsina Johari, M. Hasanuzzaman, N.A. Rahim, Modeling and performance analysis for high-rise building using ArchiCAD: initiatives towards energy-efficient building, Sustainability 14 (15) (2022) 9780, https://doi.org/10.3390/su14159780.
[47] M.T. Kahsay, G.T. Bitsuamlak, F. Tariku, Thermal zoning and window optimization framework for high-rise buildings, Appl. Energy 292 (2021), 116894, https://doi.org/10.1016/j.apenergy.2021.116894.
[48] M. El-Agami, G. Hanafy, M. Osman, Investigating the effect of high-rise Buildings' mass geometry on energy efficiency within the climatic variation of Egypt, Sustainability 13 (19) (2021) 10529, https://doi.org/10.3390/su131910529.
[49] Y.X. Ma, C. Yu, Impact of meteorological factors on high-rise office building energy consumption in Hong Kong: from a spatiotemporal perspective, Energy Build. 228 (2020), 110468, https://doi.org/10.1016/j.enbuild.2020.110468.
[50] Y.B. Yoon, B. Seo, B.B. Koh, S. Cho, Performance analysis of a double-skin façade system installed at different floor levels of high-rise apartment building, J. Build. Eng. 26 (2019), 100900, https://doi.org/10.1016/j.jobe.2019.100900.
[51] T. Saroglou, T. Theodosiou, B. Givoni, I.A. Meir, Studies on the optimum double-skin curtain wall design for high-rise buildings in the Mediterranean climate, Energy Build. 208 (2020), 109641, https://doi.org/10.1016/j.enbuild.2019.109641.
[52] A. Ahriz, A. Mesloub, L. Djeffal, B.M. Alsolami, A. Ghosh, M.H.H. Abdelhafez, The use of double-skin Façades to improve the energy consumption of high-rise office buildings in a Mediterranean climate (Csa), Sustainability 14 (10) (2022) 6004, https://doi.org/10.3390/su14106004.
[53] Y. Zhao, W. Pan, Y. Ning, Challenges for modeling carbon emissions of high-rise public residential buildings in Hong Kong, in: International Conference on Sustainable Design, Engineering and Construction, ICSDEC 2015, Elsevier Ltd, 2015, https://doi.org/10.1016/j.proeng.2015.08.494.
[54] H. Huang, W.I.B.W.M. Nazi, Y. Yu, Y. Wang, Energy performance of a high-rise residential building retrofitted to passive building standard–a case study, Appl. Therm. Eng. 181 (2020), 115902, https://doi.org/10.1016/j.applthermaleng.2020.115902.
[55] H. Sha, D. Qi, Investigation of mechanical ventilation for cooling in high-rise buildings, Energy Build. 228 (2020), 110440, https://doi.org/10.1016/j.enbuild.2020.110440.
[56] A.U. Weerasuriya, X. Zhang, V.J. Gan, Y. Tan, A holistic framework to utilize natural ventilation to optimize energy performance of residential high-rise buildings, Build. Environ. 153 (2019) 218–232, https://doi.org/10.1016/j.buildenv.2019.02.027.
[57] V.J. Gan, H.K. Wong, K.T. Tse, J.C. Cheng, I.M. Lo, C.M. Chan, Simulation-based evolutionary optimization for energy-efficient layout plan design of high-rise residential buildings, J. Clean. Prod. 231 (2019) 1375–1388, https://doi.org/10.1016/j.jclepro.2019.05.324.
[58] M. Moujahed, N. Sezer, D. Hou, L.L. Wang, I. Hassan, Comparative energy performance evaluation and uncertainty analysis of two building archetype development methodologies: a case study of high-rise residential buildings in Qatar, Energy Build. 276 (2022), 112535, https://doi.org/10.1016/j.enbuild.2022.112535.
[59] D. Yang, P. Li, Dimensionless design approach, applicability and energy performance of stack-based hybrid ventilation for multi-story buildings, Energy 93 (2015) 128–140, https://doi.org/10.1016/j.energy.2015.08.115.
[60] P. Prajongsan, S. Sharples, Enhancing natural ventilation, thermal comfort and energy savings in high-rise residential buildings in Bangkok through the use of ventilation shafts, Build. Environ. 50 (2012) 104–113, https://doi.org/10.1016/j.buildenv.2011.10.020.
[61] S. Alnusairat, P. Jones, Ventilated skycourts to enhance energy savings in high-rise office buildings, Archit. Sci. Rev. 63 (2) (2020) 175–193, https://doi.org/10.1080/00038628.2019.1685453.
[62] H. Qin, W. Pan, Energy use of subtropical high-rise public residential buildings and impacts of energy saving measures, J. Clean. Prod. 254 (2020), 120041, https://doi.org/10.1016/j.jclepro.2020.120041.
[63] H. Jang, J. Kang, A stochastic model of integrating occupant behaviour into energy simulation with respect to actual energy consumption in high-rise apartment buildings, Energy Build. 121 (2016) 205–216, https://doi.org/10.1016/j.enbuild.2016.03.037.
[64] W. Pan, H. Qin, Y. Zhao, Challenges for energy and carbon modeling of high-rise buildings: the case of public housing in Hong Kong, Resour. Conserv. Recycl. 123 (2017) 208–218, https://doi.org/10.1016/j.resconrec.2016.02.013.
[65] J.M. Zambrano, U.F. Oberegger, G. Salvalai, Towards integrating occupant behaviour modelling in simulation-aided building design: reasons, challenges and solutions, Energy Build. 253 (2021), 111498, https://doi.org/10.1016/j.enbuild.2021.111498.
[66] T. Harputlugil, P. de Wilde, The interaction between humans and buildings for energy efficiency: a critical review, Energy Res. Soc. Sci. 71 (2021), 101828, https://doi.org/10.1016/j.erss.2020.101828.
[67] X. Shi, B. Si, J. Zhao, Z. Tian, C. Wang, X. Jin, X. Zhou, Magnitude, causes, and solutions of the performance gap of buildings: a review, Sustainability 11 (3) (2019) 937, https://doi.org/10.3390/su11030937.
[68] T. El-Diraby, T. Krijnen, M. Papagelis, BIM-based collaborative design and socio-technical analytics of green buildings, Autom. Constr. 82 (2017) 59–74, https://doi.org/10.1016/j.autcon.2017.06.004.
[69] Y. Liu, S. Van Nederveen, M. Hertogh, Understanding effects of BIM on collaborative design and construction: an empirical study in China, Int. J. Proj. Manag. 35 (4) (2017) 686–698, https://doi.org/10.1016/j.ijproman.2016.06.007.
[70] H. Sun, R. Ji, W. Xie, BIM collaborative design solutions for super high-rise buildings over 250 meters, in: In 7th International Conference on Environmental Science and Civil Engineering, ESCE 2021, IOP Publishing Ltd., 2021, https://doi.org/10.1088/1755-1315/719/2/022060.
[71] F. Morales, R.F. Herrera, F.M.L. Rivera, E. Atencio, M. Nuñez, Potential application of BIM in RFI in building projects, Buildings 12 (2) (2022) 145, https://doi.org/10.3390/buildings12020145.
[72] J. Choi, J. Choi, I. Kim, Development of BIM-based evacuation regulation checking system for high-rise and complex buildings, Autom. Constr. 46 (2014) 38–49, https://doi.org/10.1016/j.autcon.2013.12.005.
[73] J. Wang, L. Hou, H.Y. Chong, X. Liu, X. Wang, J. Guo, A cooperative system of GIS and BIM for traffic planning: A high-rise building case study, in: Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), Springer Verlag, 2014, pp. 143–150, https://doi.org/10.1007/978-3-319-10831-5_20.
[74] K. Kincelova, C. Boton, P. Blanchet, C. Dagenais, Fire safety in tall timber building: a BIM-based automated code-checking approach, Buildings 10 (7) (2020) 121, https://doi.org/10.3390/buildings10070121.
[75] Z. Wang, J. Liu, A seven-dimensional building information model for the improvement of construction efficiency, Adv. Civ. Eng (2020) 2020, https://doi.org/10.1155/2020/8842475.
[76] K. Wu, B.G. de Soto, B.T. Adey, F. Zhang, BIM-based estimation of vertical transportation demands during the construction of high-rise buildings, Autom. Constr. 110 (2020), 102985, https://doi.org/10.1016/j.autcon.2019.102985.
[77] X. Shi, L. Wang, Distribution technique of green material list for high-rise building engineering in BIM technology, Math. Probl. Eng. (2022) 2022, https://doi.org/10.1155/2022/6960596.
[78] H. Omrany, V. Soebarto, J. Zuo, E. Sharifi, R. Chang, What leads to variations in the results of life-cycle energy assessment? An evidence-based framework for residential buildings, Energy and Built Environ. 2 (4) (2021) 392–405, https://doi.org/10.1016/j.enbenv.2020.09.005.
[79] H. Omrany, V. Soebarto, E. Sharifi, A. Soltani, Application of life cycle energy assessment in residential buildings: a critical review of recent trends, Sustainability 12 (1) (2020) 351, https://doi.org/10.3390/su12010351.
[80] H. Omrany, V. Soebarto, J. Zuo, R. Chang, A comprehensive framework for standardising system boundary definition in life cycle energy assessments, Buildings 11 (6) (2021) 230, https://doi.org/10.3390/buildings11060230.
[81] Y. Teng, J. Xu, W. Pan, Y. Zhang, A systematic review of the integration of building information modeling into life cycle assessment, Build. Environ. 221 (2022), 109260, https://doi.org/10.1016/j.buildenv.2022.109260.
[82] Tally, Available from, https://apps.autodesk.com/RVT/en/Detail/Index?id=3841858388457011756. Accessed: [13/11/2022].
[83] M.L. Rivera, H.L. MacLean, B. McCabe, Implications of passive energy efficiency measures on life cycle greenhouse gas emissions of high-rise residential building envelopes, Energy Build. 249 (2021), 111202, https://doi.org/10.1016/j.enbuild.2021.111202.
[84] B.S. Alotaibi, S.A. Khan, M.A. Abuhussain, N. Al-Tamimi, R. Elnaklah, M. A. Kamal, Life cycle assessment of embodied carbon and strategies for Decarbonization of a high-rise residential building, Buildings 12 (8) (2022) 1203, https://doi.org/10.3390/buildings12081203.
[85] V.J. Gan, M. Deng, K.T. Tse, C.M. Chan, I.M. Lo, J.C. Cheng, Holistic BIM framework for sustainable low carbon design of high-rise buildings, J. Clean. Prod. 195 (2018) 1091–1104, https://doi.org/10.1016/j.jclepro.2018.05.272.
[86] M.K. Ansah, X. Chen, H. Yang, L. Lu, P.T. Lam, Developing an automated BIM-based life cycle assessment approach for modularly designed high-rise buildings, Environ. Impact Assess. Rev. 90 (2021), 106618, https://doi.org/10.1016/j.eiar.2021.106618.

[87] J. Xu, Y. Teng, W. Pan, Y. Zhang, BIM-integrated LCA to automate embodied carbon assessment of prefabricated buildings, J. Clean. Prod. 374 (2022), 133894, https://doi.org/10.1016/j.jclepro.2022.133894.

[88] B. Cheng, J. Li, V.W. Tam, M. Yang, D. Chen, A BIM-LCA approach for estimating the greenhouse gas emissions of large-scale public buildings: a case study, Sustainability 12 (2) (2020) 685, https://doi.org/10.3390/su12020685.

[89] V.J. Gan, C.M. Chan, K.T. Tse, I.M. Lo, J.C. Cheng, A comparative analysis of embodied carbon in high-rise buildings regarding different design parameters, J. Clean. Prod. 161 (2017) 663–675, https://doi.org/10.1016/j.jclepro.2017.05.156.

[90] T. Potrč Obrecht, M. Röck, E. Hoxha, A. Passer, BIM and LCA integration: a systematic literature review, Sustainability 12 (14) (2020) 5534, https://doi.org/10.3390/su12145534.

[91] J. Basbagill, F. Flager, M. Lepech, M. Fischer, Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts, Build. Environ. 60 (2013) 81–92, https://doi.org/10.1016/j.buildenv.2012.11.009.

[92] C. Kiamili, A. Hollberg, G. Habert, Detailed assessment of embodied carbon of HVAC systems for a new office building based on BIM, Sustainability 12 (8) (2020) 3372, https://doi.org/10.3390/su12083372.

[93] H. Omrany, R. Chang, V. Soebarto, Y. Zhang, A. Ghaffarianhoseini, J. Zuo, A bibliometric review of net zero energy building research 1995–2022, Energy Build. 262 (2022), 111996, https://doi.org/10.1016/j.enbuild.2022.111996.

[94] H. Omrany, V. Soebarto, A. Ghaffarianhoseini, Rethinking the concept of building energy rating system in Australia: a pathway to life-cycle net-zero energy building design, Archit. Sci. Rev. 65 (1) (2022) 42–56, https://doi.org/10.1080/00038628.2021.1911783.

[95] X. Chen, J. Huang, H. Yang, J. Peng, Approaching low-energy high-rise building by integrating passive architectural design with photovoltaic application, J. Clean. Prod. 220 (2019) 313–330, https://doi.org/10.1016/j.jclepro.2019.02.137.

[96] E.D. Giouri, M. Tenpierik, M. Turrin, Zero energy potential of a high-rise office building in a Mediterranean climate: using multi-objective optimization to understand the impact of design decisions towards zero-energy high-rise buildings, Energy Build. 209 (2020), 109666, https://doi.org/10.1016/j.enbuild.2019.109666.

[97] P. Hoseinzadeh, M.K. Assadi, S. Heidari, M. Khalatbari, R. Saidur, H. Sangin, Energy performance of building integrated photovoltaic high-rise building: case study, Tehran, Iran, Energy Build. 235 (2021), 110707, https://doi.org/10.1016/j.enbuild.2020.110707.

[98] A. Alawode, P. Rajagopalan, Feasibility of net zero energy high rise apartment buildings in Australia, Sol. Energy 231 (2022) 158–174, https://doi.org/10.1016/j.solener.2021.11.030.

[99] H. Wu, F. Deng, H. Tan, Research on parametric design method of solar photovoltaic utilization potential of nearly zero-energy high-rise residential building based on genetic algorithm, J. Clean. Prod. 368 (2022), 133169, https://doi.org/10.1016/j.jclepro.2022.133169.

[100] F. Vahdatikhaki, N. Salimzadeh, A. Hammad, Optimization of PV modules layout on high-rise building skins using a BIM-based generative design approach, Energy Build. 258 (2022), 111787, https://doi.org/10.1016/j.enbuild.2021.111787.

[101] S. Alizadehsalehi, A. Hadavi, J.C. Huang, From BIM to extended reality in AEC industry, Autom. Constr. 116 (2020), 103254, https://doi.org/10.1016/j.autcon.2020.103254.

[102] V.J. Gan, T. Liu, K. Li, Integrated BIM and VR for interactive aerodynamic design and wind comfort analysis of modular buildings, Buildings 12 (3) (2022) 333, https://doi.org/10.3390/buildings12030333.

[103] N. Yabuki, K. Miyashita, T. Fukuda, An invisible height evaluation system for building height regulation to preserve good landscapes using augmented reality, Autom. Constr. 20 (3) (2011) 228–235, https://doi.org/10.1016/j.autcon.2010.08.003.

[104] S. Zhao, L. Zhang, E. DeAngelis, Using augmented reality and mixed reality to interpret design choices of high-performance buildings, in: European Conference On Computing In Construction, 2019, July, pp. 435–490, https://doi.org/10.35490/EC3.2019.142.

[105] K. Chen, W. Lu, F. Xue, P. Tang, L.H. Li, Automatic building information model reconstruction in high-density urban areas: augmenting multi-source data with architectural knowledge, Autom. Constr. 93 (2018) 22–34, https://doi.org/10.1016/j.autcon.2018.05.009.

[106] X. Huang, Research on Computer Assisted Intelligent Emission System of High-rise Building Based on BIM Technology and Wireless Automatic Monitoring. In Journal of Physics: Conference Series, IOP Publishing, 2021, November, https://doi.org/10.1088/1742-6596/2083/4/042073.

[107] D. Donath, D. Lobos, Plausibility in early stages of architectural design: a new tool for high-rise residential buildings, Tsinghua Sci. Technol. 14 (3) (2009) 327–332, https://doi.org/10.1016/S1007-0214(09)70048-3.

[108] J.M.D. Delgado, L. Oyedele, P. Demian, T. Beach, A research agenda for augmented and virtual reality in architecture, engineering and construction, Adv. Eng. Inform. 45 (2020), 101122, https://doi.org/10.1016/j.aei.2020.101122.

[109] J. Cho, C. Yoo, Y. Kim, Viability of exterior shading devices for high-rise residential buildings: case study for cooling energy saving and economic feasibility analysis, Energy Build. 82 (2014) 771–785, https://doi.org/10.1016/j.enbuild.2014.07.092.

[110] N. Ham, S. Moon, J.H. Kim, J.J. Kim, Economic analysis of design errors in BIM-based high-rise construction projects: case study of Haeundae L project, J. Constr. Eng. Manag. 144 (6) (2018) 05018006, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001498.

[111] V.J. Gan, C.L. Wong, K.T. Tse, J.C. Cheng, I.M. Lo, C.M. Chan, Parametric modelling and evolutionary optimization for cost-optimal and low-carbon design of high-rise reinforced concrete buildings, Adv. Eng. Inform. 42 (2019), 100962, https://doi.org/10.1016/j.aei.2019.100962.

[112] T. Hamidavi, S. Abrishami, M.R. Hosseini, Towards intelligent structural design of buildings: a BIM-based solution, J. Build. Eng. 32 (2020), 101685, https://doi.org/10.1016/j.jobe.2020.101685.

[113] C. Jung, R. Awad, J. Awad, A study of optimal design process for complex-shaped skyscrapers' structural systems in United Arab Emirates, Ain Shams Eng. J. 13 (5) (2022), 101683, https://doi.org/10.1016/j.asej.2021.101683.

[114] S.I. Lee, J.S. Bae, Y.S. Cho, Efficiency analysis of set-based design with structural building information modeling (S-BIM) on high-rise building structures, Autom. Constr. 23 (2012) 20–32, https://doi.org/10.1016/j.autcon.2011.12.008.

[115] D. Mavrokapnidis, C.C. Mitropoulou, N.D. Lagaros, Environmental assessment of cost optimized structural systems in tall buildings, J. Build. Eng. 24 (2019), 100730, https://doi.org/10.1016/j.jobe.2019.100730.

[116] S. Attia, M. Hamdy, W. O'Brien, S. Carlucci, Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design, Energy Build. 60 (2013) 110–124, https://doi.org/10.1016/j.enbuild.2013.01.016.

[117] W. Tian, A review of sensitivity analysis methods in building energy analysis, Renew. Sust. Energ. Rev. 20 (2013) 411–419, https://doi.org/10.1016/j.rser.2012.12.014.

[118] Z. Pang, Z. O'Neill, Y. Li, F. Niu, The role of sensitivity analysis in the building performance analysis: a critical review, Energy Build. 209 (2020), 109659, https://doi.org/10.1016/j.enbuild.2019.109659.

[119] A. Eltaweel, S.U. Yuehong, Parametric design and daylighting: a literature review, Renew. Sust. Energ. Rev. 73 (2017) 1086–1103, https://doi.org/10.1016/j.rser.2017.02.011.

[120] Census and Statistics Department, Thematic Household Survey Report no. 59, SAR, 2013.

[121] D. Ladenhauf, K. Battisti, R. Berndt, E. Eggeling, D.W. Fellner, M. Gratzl-Michlmair, T. Ullrich, Computational geometry in the context of building information modeling, Energy Build. 115 (2016) 78–84, https://doi.org/10.1016/j.enbuild.2015.02.056.

[122] D. Utkucu, H. Sözer, Interoperability and data exchange within BIM platform to evaluate building energy performance and indoor comfort, Autom. Constr. 116 (2020), 103225, https://doi.org/10.1016/j.autcon.2020.103225.

[123] US Department of Energy, Software Tools, Available from, https://www.energy.gov/eere/buildings/listings/software-tools, 2022. Accessed: [19/12/2022].

[124] DesignBuilder, DesignBuilder Optimisation, Available from, http://www.batisim.net/aide/index.html?optimisation.htm, 2022. Accessed: [19/12/2022].

[125] H. Omrany, A. Ghaffarianhoseini, U. Berardi, A. Ghaffarianhoseini, D.H. Li, Is atrium an ideal form for daylight in buildings? Archit. Sci. Rev. 63 (1) (2020) 47–62, https://doi.org/10.1080/00038628.2019.1683508.