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Article

Parametric BIM-Based Lifecycle Performance Prediction and Optimisation for Residential Buildings Using Alternative Materials and Designs

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Highlights:

What are the main findings? What is the implication of the main findings?

- Proposal of a BIM-based framework for lifecycle carbon prediction and optimisation.
- Proposal of a standard method with generic formulations to calculate the embodied carbon.
- Exploration of BIM-enabled parametric modelling for optimising low-carbon alternative design.
- Exploration of the interoperability between BIM and energy simulation for lifecycle energy analysis.
- Investigation of low-carbon materials and designs in the lifecycle carbon of residential buildings.

Abstract: Residential building construction is resource-intensive and significantly impacts the environment by embodied and operational carbon emissions. This study has adopted a parametric building information modelling (BIM)-based approach for a residential building to analyse its lifecycle carbon performance and to evaluate the optimisation potential through alternative material use and design. The study looks at a residential development project, applying an automatic calculation and analysis tool of upfront embodied carbon and BIM-based lifecycle energy simulation to predict carbon emissions from operating the built spaces. A parametric BIM model has been established to aid energy simulation and operational carbon assessment across a 50-year building lifetime, considering 1.5 °C Net-Zero World and 3 °C Hot House World climate scenarios. Various improvement opportunities for future residential development projects, from material selection to operational efficiencies, are explored. This includes quantitative analysis on architectural-structure design, low-carbon construction materials (e.g., cement substitutes, steel scraps, and green hydrogen steel), and novel design for construction approaches (such as modular integrated construction), with discussion around their impacts on optimising the building lifecycle carbon performance. This study provides a deeper understanding and insights into the lifecycle performance of residential buildings to facilitate further exploration of achieving a more sustainable and low-carbon built environment.

Keywords: building information modelling; predictive analysis; optimisation; building energy efficiency; construction materials; prefabrication; embodied carbon; building lifecycle

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1. Introduction

Buildings account for around one-third of global greenhouse gas (GHG) emissions and 40% of the world's energy usage [1]. According to studies conducted by the U.S. Department of Energy, low-carbon green buildings use 25% less energy and produce 34% lower GHG emissions [2]. Understanding the whole-life carbon emissions of buildings is an important step to developing corresponding reduction measures for achieving net-zero emissions [3]. Emissions associated with the manufacturing of materials account for around 40% of the lifecycle GHG in buildings. In contrast, the most significant portion of building emissions is generated by building lifecycle activities, such as operating built spaces, accounting for 52% of the lifecycle emissions. To align with the 1.5 °C goal of the Paris Agreement, there has been a significant increase in the number of green buildings over the years following the unique climate conditions and social and economic priorities across the world as an effort to reduce the negative impact and improve resilience in the environment through more sustainable material adoption and reduced energy consumption [4,5].

Lifecycle thinking and quantitative assessment are important tools for understanding a building lifecycle's carbon emissions. Adopting a long-term perspective can provide holistic understanding of the environmental impacts and potential economic gains, allowing better integration of low-carbon design [6]. Hybrid data quality assessment methods are proposed to present the results of environmental models. Combining the quantification of accuracy and reliability of the input data, they allow for more informed decision making and support the identification of improvement areas [7]. With the rapidly evolving technological advancement in recent years, there has been a rising interest in innovative digital technologies such as BIM in the field of sustainable buildings. BIM is an emerging tool that is becoming widely used by professionals in the architectural, engineering, and construction industries. Industry Foundation Classes (IFC), as an open file format for BIM models and facilitates a shared data environment where various stakeholders can input model-related information at different building stages [8], enabling collaboration between project owners/developers, architects, contractors, and engineers. Coupled with BIM technology, parametric modelling has a high potential to benefit building lifecycle performance prediction and optimisation significantly. Exploration and the best design selection for buildings can be carried out by varying the building parameter set and their relationships [9]. The current research also regards BIM as the core data model for analysing building performance, mainly in the automated preparation for building energy modelling (BEM) [10]. BEM tools allow for a more advanced evaluation of building performance, including locations and geometry, construction and space, thermal zones, occupancy, equipment, lighting loads, HVAC systems, and energy simulations. With the accelerated urbanisation in the built environment, it is crucial to capitalise on emerging technologies through a better understanding of the factors that can influence a building's lifecycle performance in ensuring a more efficient and sustainable built environment in the long run [11].

Some studies have tried to combine BIM with computational fluid dynamics and energy performance simulation to assess energy conservation opportunities [12–14]. In the process of architectural design, Weerasuriya et al. [15] proposed the BIM application required to transform the BIM building model geometry for generating the meshes and computational domain for fluid dynamics simulation and lifecycle energy prediction. Based upon the BIM platform, Gan et al. [16] further coupled the numerical simulation with generative algorithms to explore the optimal energy-efficient design for residential buildings. Here, the performance assessment's computational domain and boundary conditions may be created using BIM's detailed geometry and project-based information. Aside from simulation-based performance optimisation, BIM has been leveraged to synchronise the real-time built environment data for lifecycle performance analysis. This involves using building management systems to monitor facilities and extract state measurements from smart sensors [17]. BIM offers 3D visualisation and detailed semantic data on the building context, including facility geometry, properties, spatial relationships, and connectedness [18]. Building models that use BIM may theoretically be created in software programmes and contain various data, including building geometry, materials, cost, maintenance, and operation schedule. If the BIM entities can include the real-time sensor metadata, such a "static" model becomes a real-time information model for optimisation of lifecycle performance [19]. The key to maintaining smooth data transfers is the secure interoperability of multi-discipline data across BIM and sensor fields without missing or mistaking information, which brings us to the strategic significance of having an efficient data exchange format [20,21]. IFC is often used in BIM models to define a building's physical and functional attributes [22]. In contrast, data communication protocols and semantic models allow information flow between smart sensing devices [19]. Once the built environment data are obtained, the next step is to use the data in supporting operational optimisation, considering the constraints to operating the built space. Some researchers [23] have adopted data-driven modelling and predictive control for smart building management. Precisely, Shaikh et al. [24] reported the energy and comfort management methods via building control optimisation, whilst another study [25] presented the application of computational intelligence to underpin the optimisation of mechanical ventilation and air conditioning (MVAC). In previous studies, the centralised optimisation models required facility operation decisions to be made by a central system, which is computationally complex for extensive facilities. In these settings, there is a growing interest in the decentralised multi-agent system (MAS) paradigm [17]. Previous studies have explored the MAS-based subjective model for indoor adaptive thermal comfort and building automation [26,27]. While the earlier studies deepened the understanding of smart building performance optimisation, the decision making was mostly limited to a small sole objective, which made it less adaptive to modern building operations. This calls for a new parametric BIM study to explore buildings' influential factors on the constructed facilities' lifecycle performance.

Aside from operational energy conservation, BIM has been used to facilitate the calculation and mitigation of embodied carbon. The embodied carbon of construction materials has been discovered to be a substantial contributor to the total carbon emissions of a built structure. The carbon footprint associated with the manufacturing stage of major construction materials, which include concrete and steel, can account for 40% of the lifecycle carbon emissions [28]. BIM-based digital technologies make it easier to automatically take off material quantities and help evaluate a building's embodied carbon performance [29]. Material information and model geometry can be extracted from the BIM platform for the parametric assessment of embodied carbon in the early stage of project development [30,31]. Such research also provides systematic insights into the embodied carbon emissions of prefabricated buildings [32]. Semantic web technologies have been added to the BIM application to provide lifecycle assessment (LCA) of cradle-to-site CO_2 emissions [33]. The integrated use of generative design in BIM allows for a rule-based approach in evaluating design alternatives via an in-built visual programming language in BIM software. This is particularly useful during construction projects' planning and design stage through visualisation and optimisation of the layout to maximise its benefits and requirements. Gan [34] proposed the usage of IFC model view definition (MVD) to visualise BIM-based graph data for prefabricated modules during the design stage of constructing modular buildings. Reference [35] suggested BIM-based 3D geometric modelling and generative algorithms to automatically calculate the embodied carbon and cost of high-rise structures based on the embodied carbon assessment. Design optimisation approaches and algorithms have been investigated to enable spatial planning or architectural-structure optimisation for minimising embodied energy/carbon [36,37]. Several studies [38,39] combined finite element modelling with genetic algorithms (GAs) for optimum structural designs while considering embodied carbon reduction and constructability restrictions.

Researchers have now improved lifecycle performance optimisation using machine learning thanks to the development of neural network computing. Deep learning algorithms are further linked with generative modelling approaches, enabling a more sophisticated search for the best design. Layout optimisation was carried out using a generative adversarial network, which searches for candidates while a discriminator assesses the possibilities created [38,39]. Ghannad and Lee [40] employed generative design through the coupled generative adversarial network (CoGAN) and vectorising generated modular placements to develop a new framework for generating flexible module layouts according to input criteria. In this regard, machine learning learns from the problem structure to help control the optimum searching process. The integrated use of generative design in BIM allows for a rule-based approach in evaluating design alternatives via an in-built visual programming language in BIM software. With a strategic focus on design for manufacturing and assembly (DfMA) procedures to improve construction efficiency, there is a greater need to study how the design of modular buildings can be better optimised. Sydora and Stroulia [41] proposed a generative algorithm for the automation of interior objects through various sets of attributes, layout rules, and relationships that have been predetermined between objects. The generated design is also evaluated through rule-based checking to verify the optimised model. Previous research has concentrated chiefly on design solutions for decreasing the operational carbon or material optimisation for minimal embodied carbon. The potential for combining alternative materials and design features was not extensively investigated. This study noted that many design factors can affect the building lifecycle carbon footprint and energy consumption and understood that it is imperative to develop a framework to study the potential of energy conservation and carbon reduction and the influential factors across different alternative materials and design features through the parametric BIM-based approach.

This article presents a parametric BIM-based framework for predicting and optimising the lifecycle carbon performance in residential buildings, combining alternative material use and design strategies to achieve significant carbon reduction. The proposed framework incorporates building information throughout various project development phases and leverages BIM and energy simulation tools to evaluate the impacts of different materials and designs on a building's lifecycle carbon performance. The study demonstrates the potential of this methodology for promoting lifecycle-oriented low-carbon building design and offers insights into energy conservation and carbon reduction strategies. Below is a list of academic contributions:

- Firstly, a system workflow for lifecycle carbon prediction and optimisation is proposed in this study. The proposed workflow integrates building information from various project development phases such as project inception, conceptualisation, criteria definition, design, implementation, operation, and maintenance. It enables assessment and analysis of building performance throughout its lifecycle, enhancing the ability to predict and optimise carbon emissions.
- Secondly, a standard method with generic formulations is proposed to calculate and analyse the upfront embodied carbon. The present study generalises the formulation and emission factors for evaluating the material embodied carbon, contributing to improved carbon performance prediction and optimisation.
- Thirdly, BIM-enabled parametric modelling is explored for optimising and analysing low-carbon alternative design. The crucial variables influencing lifecycle energy consumption in buildings, such as geometrics and structural layout, spatial planning, and building usage pattern, suggest a BIM-based energy modelling technique to contrast various building usages for energy conservation. The BIM-enabled parametric modelling approach allows for exploring alternative materials and designs and evaluating their impacts on the building's lifecycle carbon performance. This process provides valuable insights into optimal design strategies and their contributions to reducing the building's carbon footprint.
- The data interoperability between BIM and energy simulation for lifecycle energy performance analysis is explored. Improving the interoperability between BIM and energy simulation tools enhances the recovery of the BIM digital model, minimising the risk of data loss during data transfer, and addresses compatibility issues between platforms. This integration enables a more precise assessment of energy conservation potential and influential factors in residential buildings, contributing to practical carbon assessment and analysis development.
- Lastly, the present study investigates low-carbon materials and design alternatives for the lifecycle carbon footprint of residential buildings. This involves the usage of cement substitutes, steel scraps, and green hydrogen steel and the application of DfMA and modular construction to mitigate the carbon footprint of residential buildings. The carbon emission hotspots have also been identified with a comprehensive data

analysis. Findings relevant to energy conservation and carbon reduction can inform future residential development.

2. Methodology

This section presents the parametric BIM-based lifecycle carbon performance prediction and optimisation for residential buildings. The proposed BIM-based framework follows the procedure and information flow during the project development phases. The information flow and interaction between various stakeholders throughout different project phases are shown in the process map. Additional steps of the process map would incorporate building information to assess building performance accurately. This links the components involved in lifetime performance prediction. The process map can be used to establish property extension in the BIM domain and indicate essential cooperation for building performance prediction. A standardised framework for categorising the phases in a building's lifecycle is adopted to guarantee that information is organised correctly. Stakeholders from four disciplines are represented in the process map, and there are seven significant phases: project inception, conceptualisation, criteria definition, design, implementation, operation, and maintenance.

The generic formulation for embodied carbon calculation is established. A BIM model which contains the structural elements and non-structural components is created. Each building component in the BIM model is characterised by project-related information, such as the building material type and its thermal and mechanical properties, for the lifecycle energy performance prediction. Alternative materials and designs are tested to study their impacts on the building lifecycle performance, providing insights into the optimal design and its contribution to the carbon footprint. The present study leverages average emission factors of typical materials, focusing on streamlining the BIM workflow for sustainability analysis. Details about the methodology are described in the following subsections.

2.1. Automated Embodied Carbon Calculator

2.1.1. Formulation for Embodied Carbon Assessment

The building chosen for the study is Eight Star Street, a residential building in Wan Chai, Hong Kong. The building is a 21-storey residential tower above a 5-storey podium with a 3-storey roof. The lower storey comprises the main entrance, amenities, and retail shops, whereas the residential floors span from 2/F to 25/F. The building consists of thirty-seven apartments with a vast collection of layouts ranging from one- to three-bedroom units. The total construction floor area is 3130 m^2. The residential building is constructed mainly from reinforced concrete using a shear wall structure, which provides the lateral stability of the building. The amounts of building materials and energy sources used in the construction are shown in Table 1.

Table 1. Consumption of materials and energy for the residential building in the analysis.

Materials or Energy	Recycled Content	Amount	Unit
Concrete (Grade 15/20D 75 mm)	No PFA	13	m^3
Concrete (Grade 20/20D 75 mm)	1.5% PFA	18	m^3
Concrete (Grade 30/20D 125 mm)	2.0% PFA	19	m^3
Concrete (Grade 45/10D 125 mm)	2.30% PFA	5	m^3
Concrete (Grade 45/20D 125 mm)	2.40% PFA	216	m^3
Concrete (Grade 45/20D 125 mm WP with Caltite)	2.40% PFA	192	m^3
Concrete (Grade 60/20D 200 mm)	2.6% PFA	2456	m^3
Concrete (Grade 60/20D 200 mm WP with Caltite)	2.6% PFA	1017	m^3
Reinforcement Bar	Virgin	1,109,070	kg
Timber	N/A	151	m^3
Glass for Curtain Wall	Virgin	42,700	kg
Aluminium	Virgin	96,261	kg
Electricity	N/A	210,906	kWh

The evaluation of upfront embodied carbon is based on a cradle-to-site process, which necessitates evaluating emissions from manufacturing the construction materials, moving those materials to the site, and the associated on-site construction activities. The three main GHGs that make up carbon emissions are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The CO_2 equivalent (CO_2-e) of various carbon emissions is calculated using their global warming potentials and summed up for the upfront embodied carbon (tonne CO_2-e). The embodied carbon is divided by the construction floor area of the building to level the upfront carbon emissions intensity (tonne CO_2-e/m^2). The following examples provide the formulas for embodied carbon assessment.

(1) **Upfront Carbon Emissions of Construction Materials**

The carbon footprint created during material manufacture and transportation is included in the assessment. The formula to determine the upfront carbon emissions of construction materials is shown below with reference to [31]:

$$E_1 = \sum_{i=1}^{I} Q_i EC_i + \sum_{i=1}^{I}\sum_{j=1}^{J} Q_i D_{i,j} TE_j \quad (1)$$

where E_1 represents the upfront carbon emissions of construction materials, Q_i is the construction material quantity (in kg), EC_i refers to the emission factor (kg CO_2-e/kg), $D_{i,j}$ is the transportation distance using a specific transport mean j (km), and TE_j represents the transportation emission factor (in kg CO_2-e/tonne·km). The material emission factors utilised in the case study are summarised in Table 2.

Table 2. Embodied carbon emission factor for different building materials.

Major Construction Materials	Emission Factor		Data Source
Concrete (Grade 15)—No PFA	247	kg CO_2-e/m^3	EF from [42]
Concrete (Grade 20)—1.5% PFA	260	kg CO_2-e/m^3	
Concrete (Grade 30)—2.0% PFA	289	kg CO_2-e/m^3	
Concrete (Grade 35)—1.8% PFA	309	kg CO_2-e/m^3	
Concrete (Grade 45)—2.3–2.4% PFA	347–348	kg CO_2-e/m^3	
Concrete (Grade 60)—2.6% PFA	394	kg CO_2-e/m^3	
Concrete (Grade 80)—3.0% PFA	462	kg CO_2-e/m^3	
Reinforcement Bar—Virgin	2.27	kg CO_2-e/kg	EF from [43]
Reinforcement Bar—30% BF-BOF	1.85	kg CO_2-e/kg	
Reinforcement Bar—100% EAF	0.55	kg CO_2-e/kg	
Reinforcement Bar—Green Hydrogen Steel	0.33	kg CO_2-e/kg	EF from hydrogen steel [44] and rebar processing [43]
Timber	1.97	kg CO_2-e/kg	EF from [45], using a density of 570 kg/m^3. Reuse: 3 times
Glass	1.20	kg CO_2-e/kg	The carbon emission factor for float glass is 0.94 kg CO_2-e/kg glass from data provided by manufacturers. To factor in the speciality glass used in buildings and the energy sources of different suppliers, the actual emission factors can be as high as 1.2 kg CO_2-e/kg
Aluminium	1.51	kg CO_2-e/kg	The carbon emission factor for aluminium end products (curtain wall, window frame, ceiling, etc.) ranges from 20–490 kg CO_2-e/m^2, with reference to literature such as [46,47] and internal communications with suppliers. This amounts to 0.09–2.56 kg CO_2e/kg end products, assuming a standard density of 2710 kg/m^3; 1.51 kg CO_2-e/kg taken in the calculation is an arithmetic mean or average of the EFs for different end products
Electricity	0.71	kgCO_2-e/kwh	EF from [48]
Road Transportation	0.204	kg CO_2-e/tonne·km	EF from [49]
Railway	0.017	kg CO_2-e/tonne·km	
Marine Shipment	0.048	kg CO_2-e/tonne·km	

(2) **Carbon Emissions from Construction Activities**

Carbon emissions may arise from various on-site construction activities (E_2), and the amount can be calculated as:

$$E_2 = \sum_{e=1}^{E} Q_e EE_e \quad (2)$$

in which Q_e is the consumption of fuel or electricity for different types of construction activities, and EE_e stands for the fuel or electricity's carbon emission factors (see Table 2).

(3) **Carbon Emissions due to Waste Disposal and Sewage Treatment**

The calculation and analysis should also consider the carbon emissions produced by sewage treatment and disposal of building waste. This should consider the carbon emissions produced by large trucks used to remove construction debris. In addition, the amount of power consumed for treating sewage and fresh water should be determined as follows:

$$E_3 = \sum_{w=1}^{W} \sum_{j=1}^{J} Q_w D_{w,j} TE_j + S \times (f_1 + \varepsilon f_2) \quad (3)$$

where E_3 is carbon emissions brought on by the treatment of sewage and fresh water as well as the disposal of waste. Q_w refers to the construction waste amount (kg), transportation distance $D_{w,j}$ is expressed as km, and TE_j refers to the transportation emission factor (kg CO_2-e/tonne·km). S is the amount of water consumed for the construction (m^3), f_1 and f_2 are the emission factors for freshwater and sewage processing, respectively (kg CO_2-e/m^3), ε is the proportion of fresh water entering the sewage system. An automatic embodied carbon (EC) calculator is created using site-specific data. It reads the consumption of building materials to calculate carbon emissions automatically. Three categories, i.e., direct GHGs, indirect GHGs (energy-related), and other indirect GHGs, as defined by the GHG Protocol, are used to indicate the calculated carbon emissions.

2.1.2. Validation of Embodied Carbon Calculation

The automated EC calculator is used to assess the carbon emissions from the residential building, as shown in Figure 1. Over 94% of the upfront embodied carbon among all construction materials is contributed by rebar and concrete. More specifically, concrete provides 35% of the total material carbon footprint, with Grade 60 concrete making up around 31%. Rebar accounts for roughly 58.6%. Despite being significantly less prevalent than rebar and concrete in the project, timber, glass, and aluminium account for 1.5%, 0.3%, and 3.38% of the total upfront carbon emissions from construction materials, respectively. According to the World Business Council for Sustainable Development, façades can contribute up to 31% of the embodied carbon of a building. Façades contain steel and glass/glazing units, which, in this study, are measured separately. When calculating the material embodied carbon, glass is separated from the façade system and measured individually as one material to reveal its actual impacts. Compared to rebar and concrete, glass is essentially minimal.

After the embodied carbon of the residential building is evaluated using the EC calculator, the results are validated with a carbon assessment tool [50] ("CIC tool"), which was created to establish a platform for the evaluation of the carbon performance of buildings and infrastructure in Hong Kong. The CIC tool considers cradle-to-site carbon emissions from the extraction of raw materials to the end of the construction. The same site-specific material and construction data are input into the CIC tool to form a basis for comparing the results generated by the EC calculator. The CIC tool enables projects to report the actual performance of variables such as materials, temporary works, and site impacts. It can also demonstrate the project performance against forecast and industry benchmarks. To allow a quantitative comparison of the results between our EC calculator and the CIC tool, the data are presented in Table 3.

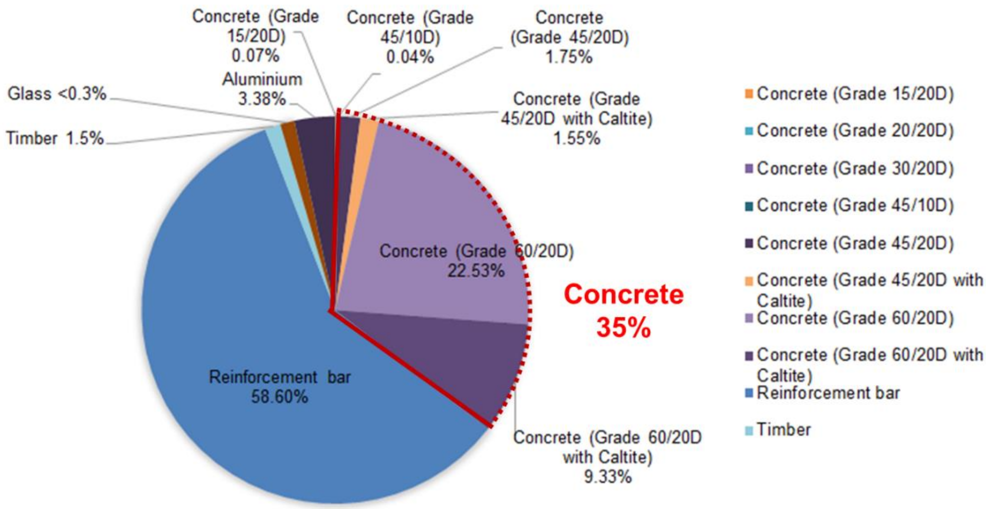


Figure 1. Breakdown of upfront carbon emissions for construction materials.

Table 3. Quantitative comparison of cradle-to-site carbon emissions.

Scope of Embodied Carbon	**EC Calculator (Tonne CO_2-e)**	**CIC Tool (Tonne CO_2-e)**
Scope (1)—Direct emissions	N/A	N/A
Scope (2)—Indirect emissions (energy-related)	149.7	168.7
Scope (3)—Other indirect emissions	4369.9	4857.4
3.1 Upfront embodied carbon emissions of construction materials	4296.0	4852.0
Concrete	1525.3	1822.0
Rebar	2517.6	2620.0
Timber	56.5	67.0
Glass	51.2	343.0
Aluminium	145.4	N/A
3.2 Carbon emissions from the transportation of construction materials	71.8	N/A (CIC tool integrates transportation emissions with embodied carbon)
Concrete	31.9	
Rebar	25.4	
Timber	0.25	
Glass	4.4	
Aluminium	9.8	
3.3 Carbon emissions due to waste disposal and sewage treatment	2.3	5.4
Total carbon emissions (tonne CO_2-e)	4519.7	5025.0
Per construction floor area (tonne CO_2-e/m^2)	1.44	1.61

Carbon emissions data from the EC calculator generally agree with those generated by the CIC tool. The indirect emissions greatly outweigh other sources, and most of the embodied carbon comes from upfront materials emissions. However, the discrepancy between the assessment results is 10.5% higher from the CIC tool than the results produced by the EC calculator. A thorough analysis of the emission factor of major construction materials is conducted to determine the underlying reasons for the difference in the results. As shown in Table 4, the emission factors for normal concrete without admixtures and cement substitutes are higher in the CIC tool. This might be caused by the methodology adopted in the CIC tool, which averages out the best and worst possible options from different material suppliers. Another comparison of the carbon emission factors for steel rebar is also conducted, as shown in Table 5. The rebar emission factor in our EC calculator is calculated based on the steel production methods such as electric arc furnace (EAF) or blast furnace–basic oxygen furnace (BF-BOF). It could be adjusted subject to the recycled scrap content and furnace type, allowing for high customisability in the carbon computation.

However, the categorisation for steel rebars in the CIC tool is not specific to the steel production technology, and the recycled content is designated into three categories, namely low, average, and high. The combination of these factors demonstrates that the concrete and steel rebar emission factors in the CIC tool are higher than the ones in the EC calculator, which might have caused the CIC tool to generate comparatively higher carbon emissions for the same project data. These issues when selecting the material type might affect the prediction accuracy, and diligence should be taken when choosing the material type in proximity for project data entry to minimise the discrepancy.

Table 4. Comparison of concrete emission factors used in the calculation.

Concrete	EC Calculator (kg CO_2-e/m^3)	CIC Tool (kg CO_2-e/m^3) [a]
Grade 20	260	309
Grade 30	288	345
Grade 35	309	367
Grade 40	335	391
Grade 45	348	427
Grade 50	365	453
Grade 60	394	467

[a] The EFs are obtained from [50], accessed in February 2023.

Table 5. Comparison of steel emission factors used in the calculation.

EC Calculator		CIC Tool	
Steel Category	Emission Factor (kg CO_2-e/tonne)	Steel Category	Emission Factor (kg CO_2-e/tonne) [a]
BF-BOF (no scraps)	2270	General reinforcement bar	2145
EAF (no scraps)	1700	Low recycled content (0–29%)	2362
BF-BOF (30% scraps)	1830	Average recycled content (30–59%)	1860
EAF (100% scraps)	550	High recycled content (≥60%)	1358

[a] The EFs are obtained from [50], accessed in February 2023.

2.2. BIM-Based Operational Carbon Assessment

BIM-supported energy simulation is performed to predict the lifecycle performance of the residential building. This is carried out by identifying influencing factors, 3D BIM, and performing interoperable information exchange between BIM and energy simulation. Before energy simulations, parameters such as construction materials and facilities' operation (HVAC, lighting, and miscellaneous equipment) are set.

2.2.1. Identification of Influential Factors

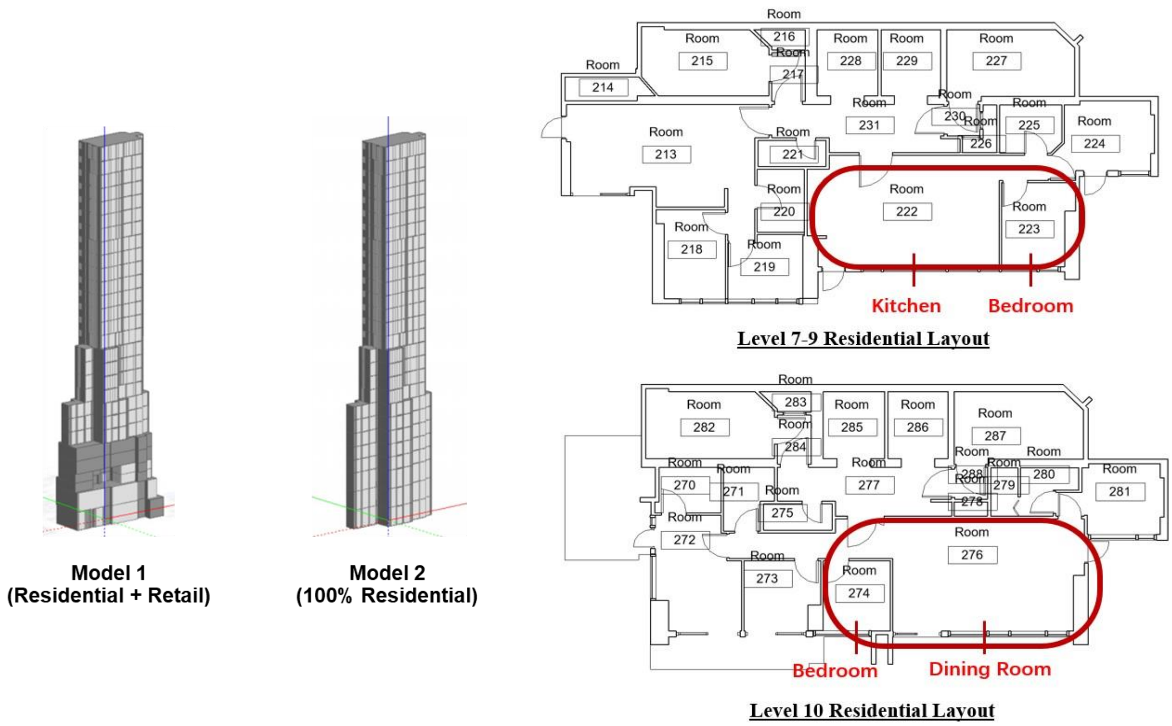
Identifying and determining the influential factors that can affect a building's energy consumption are crucial. While there have been various influencing factors presented in the literature, there are other factors that have not been considered much in the parametric BIM, namely geometrics, structural layout, spatial planning, and building usage patterns. Geometric and structural layout, as well as spatial planning, are covered in BIM, while building usage pattern is addressed in the energy simulation.

- **Geometrics and structural layout** consist of the placement, orientation, shape, and size of the building elements, as well as the type of materials and their properties such as the U-value of the curtain walls, boundaries' definition of the materials from room to room and floor to floor.
- **Spatial planning** refers to the different space usages defined for each room in the building. It also includes each building's floor layout and space organisation. It involves optimising space for different functions to meet the various requirements of the stakeholders. Additionally, building orientations play a big part in building energy consumption, as a building can attain energy savings by maximising daylighting and minimising heat gain.

- **Building usage pattern** mainly refers to the varying demand of energy consumption parameters from HVAC systems, lighting, miscellaneous equipment, domestic hot water consumption, etc. in the building. For HVAC systems, it refers to the type of cooling system such as a VRF system or split AC system. It also takes into consideration ventilation-related parameters such as the rate of airflow. For a lighting system, the type of lighting, its fixture, and lux value are essential, influential factors affecting energy consumption. Regarding miscellaneous equipment, the electrical load of each piece and the heat emitted from the equipment can affect energy consumption.

2.2.2. Parametric BIM

Upon identifying influential factors, it is essential to consider how to factor in each of the significant factors and their interdependencies for parametric modelling. The model is constructed with a level of details (LOD) of 300 for most elements. The LOD is to define the amount of building information that needs to be incorporated in a BIM model. In this paper, the developed BIM model includes the primary structural components such as beams, columns, walls, floor slabs, and other building elements such as stairs and façades. Parametric relationships in BIM can come in various forms. Figure 2 shows two BIM models for the residential building created. Model 1 is a mixed development by design, in which lower storeys are retail and Levels 2 to 25 are residential floors with 37 apartments. The residential floor plan varies. An alternative BIM model (Model 2) with all the spaces fully utilised as the residential floors is created to perform a different energy simulation to investigate the impact of the various influential factors. To do so, Model 2 converts the existing retail floors in the lower section into residential units.



(**a**) (**b**)

Figure 2. (**a**) Overview of Models 1 and 2 and (**b**) comparison of room layout for different storeys.

In terms of geometric and structural parametric relationships, the model's structural integrity stays consistent throughout the building. Some levels share a common layout plan, retaining the geometric and structural parameters throughout the whole building. With the floor area decreasing as the height of the building increases, the bottom-up modelling workflow aids in retaining the structural integrity of the same existing elements as the modelling moves up. This forms some interdependency between the bottom floor and the upper floor. The building is modelled upwards as the bottom floor has a larger area with more structural elements. The unrequired elements are removed according to the floor layout on the higher levels. This improves efficiency in regenerating the BIM model, which has a similar structural layout but differing space usage.

Regarding spatial parametric relationships, there are changes in spatial planning throughout the floors, translating to a change in space usage. For instance, while the structural layout, as highlighted in Figure 2, largely remains in residential Levels 7–9, the highlighted rooms are used for the kitchen and bedroom. However, moving to Level 10, the space layout changes into bedroom and dining room use. Therefore, space organisations could change bottom-up even though the structural design remains. Considering the factors mentioned above and considering them for the parametric modelling of 3D BIM can greatly improve efficiency in constructing the 3D model as their relationship and interdependencies are understood.

2.2.3. Interoperable Exchange between BIM and Energy Simulation

The analytical model is crucial in the transition process of exporting the model and its parameters into energy simulation software to ensure adequate energy analysis. Figure 3 presents limit elements as set to be room boundaries. Then, limit offsets are defined for each room to create limit parameters for computations of areas and volumes, which aid in making the analytical model.

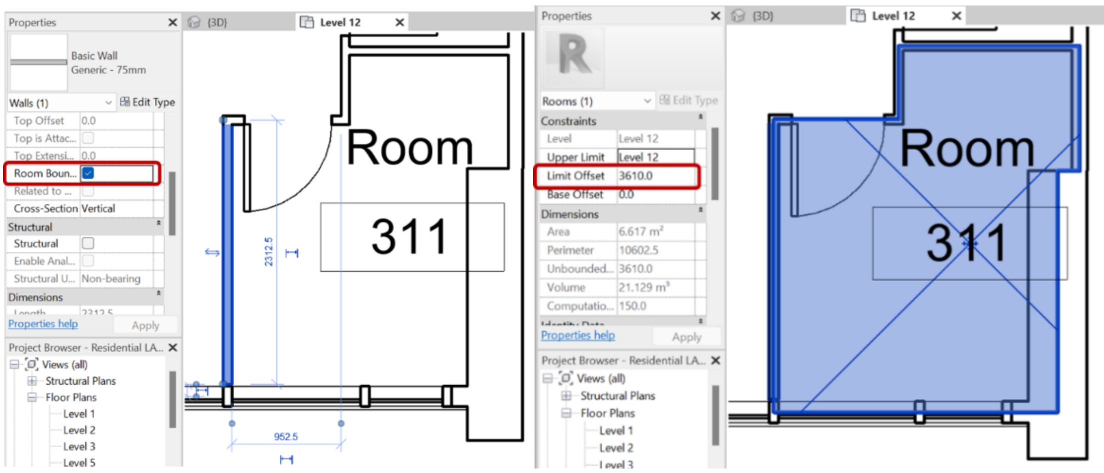


Figure 3. Room bounding setting for a wall (left) and limit offset setting for a room (right).

To ensure the retainment of BIM models for lifecycle energy prediction, two methods are used to facilitate the interoperable information exchange between BIM and energy simulation software and to aid in resolving the issues brought by the incompatibility. This study involves exporting the BIM model through green building XML (gbXML), an industry standard for storing and exchanging building information. The rooms and their defined elements, which comprise gbXML data, are exported from BIM.

- Firstly, rectifying incompatible and missing elements and redefining parameters are performed to recover data lost through the transfer. There are glasses modelled in BIM along the external façade, but they could not be detected as a transparent element in energy simulation because they are opaque. Such glazed elements are remodelled using the window functions to retain their properties, as highlighted in Figure 4. There are also green shadings after importing BIM models. Some of the green shadings appeared to reflect architectural elements that are hanging and do not take part in forming the model enclosure, making them dispensable in energy simulation. This discrepancy is due to the inability of energy simulation to identify thin elements with zero thickness. The green shadings can be eliminated by removing the BIM element.

- Secondly, direct remodelling is carried out in the energy simulation software to minimise the risk of data loss and interoperability issues during the data transfer. This is essentially carried out by adding and removing Model 1 to regenerate the full-residential Model 2. For example, LG, G, and Level 1 have heights of 5010 mm, Levels 2 to 25 have heights of 3160 mm, and Level 25 to the roof has a height of 4000 mm. The total height of the model adds up to around 102,010 mm. Elements in Model 2 need to be modified in energy simulation software, and then each room in the model is zoned to include the residential features. Then, the building usage parameters are loaded to obtain the completed analytical model.

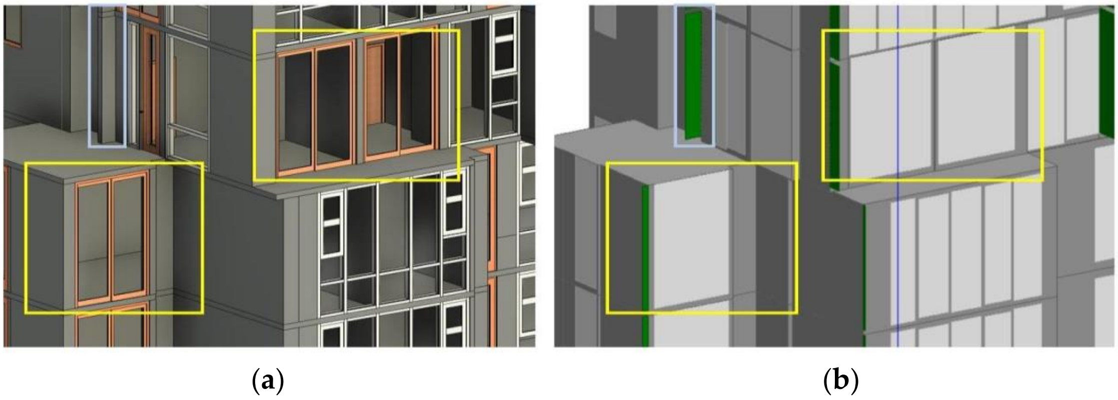


Figure 4. Comparison between elements in the original BIM model (**a**) and revised analytical model (**b**).

After the above rectification and direct remodelling methods, the analytical model can be recovered. The relevant building usage parameters are loaded into energy simulation software which covers building locations, construction materials, and system operation parameters. For each model, cooling, lighting, equipment, and domestic hot water parameters are set according to the users' information and building service standards. This study explores the different parametric settings, including some settings for locations, construction (such as the composition layers of walls), openings (such as windows), and activity settings, which are kept as the default. Figure 5 summarises the settings used for the parametric assessment of energy consumption. The HVAC system is set to split A/C for residential units with coefficient of performance (COP) defined at 2.6. The HVAC system for retail floors is set to a variant refrigerant flow (VRF) system. Corridors, lifts, staircases, and mechanical and electrical rooms have only mechanical ventilation. The energy intensity for domestic hot water, miscellaneous equipment, lighting, pump, and lifts is leveraged in the energy modelling. Thereafter, data for energy consumption across Models 1 and 2 are compared to determine the difference between the energy consumption of mixed-development and full-residential use.

2.2.4. BIM-Based Energy Simulations

This section presents results from the BIM-based energy simulation. Since the cooling load is heavily influenced by air temperature, Figure 6 illustrates the temperature and heat gain breakdown for the energy simulation. Cooling consumption from May to September is the highest as summer temperatures strongly affect energy consumption. Cooling load is the lowest from December to February due to the influence of winter temperatures. Additionally, solar radiation transfers heat into a room through the building envelope. In summer, when the temperature is high, solar radiation is transmitted through glazed windows, increasing the cooling load, and explaining the high cooling energy consumed. During winter, solar radiation is also injected through the building envelope, but its amount is generally lower compared to summer, explaining the lower cooling energy. Other equipment and systems such as lighting, miscellaneous equipment, hot water, pump, and lift are not directly affected by outdoor air temperature and solar radiation, which explains the minimal change in energy consumption. The similarity in the two models could be attributed to the fact that the retail portion only takes up a small percentage (6 out of the 27 floors) of the whole building. If the residential and retail proportions are adjusted, there is a potential for different results in energy consumption as there will be variations in the energy demands.

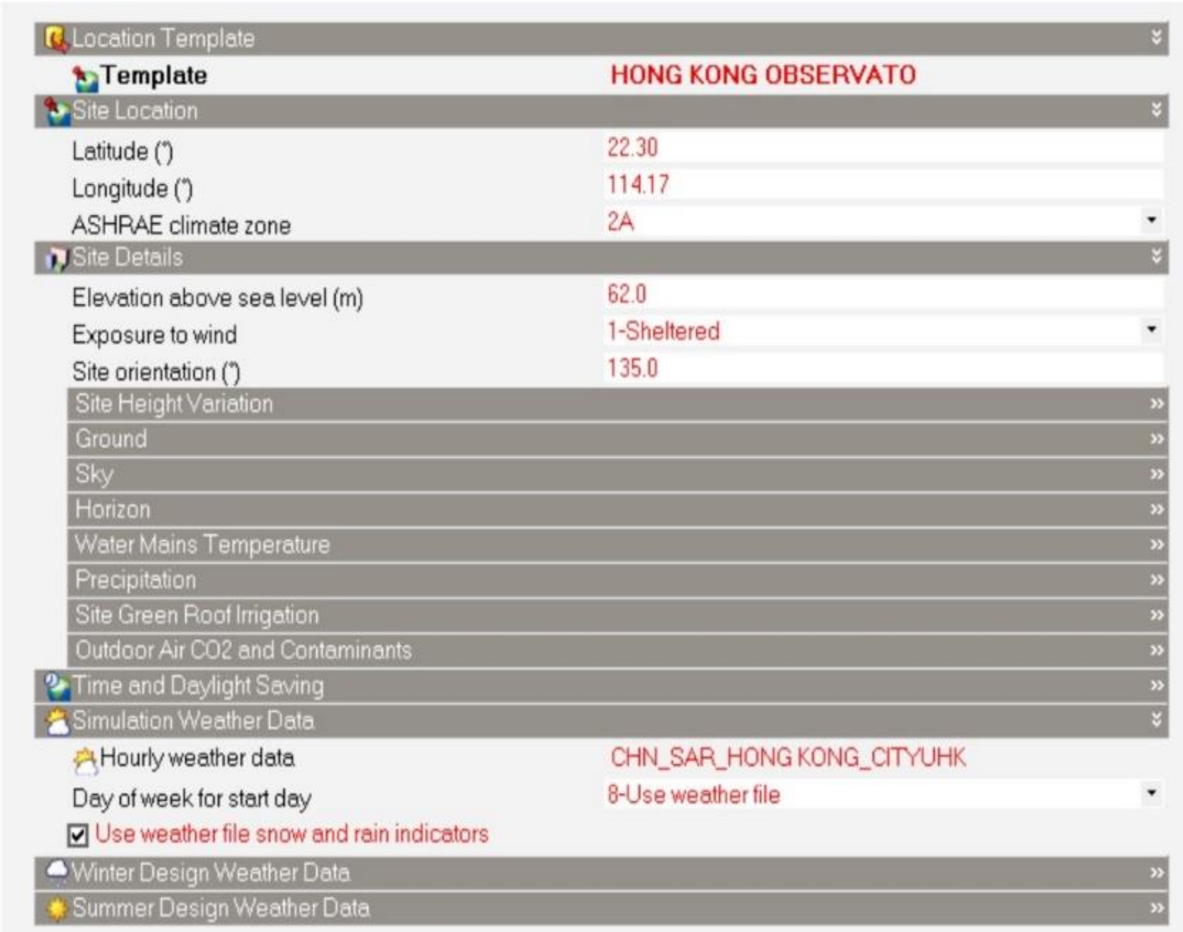


Figure 5. Location settings for energy modelling.

Figure 7a,b show the variations in energy consumption in Model 1 and Model 2. Energy consumption in both mixed-development and full-residential use peaks from May to September during summer and hits its lowest level from December to February in winter. The total annual energy consumption is 922 MWh for Model 1 and 759 MWh for Model 2. While the results show similarity in pattern, the mixed-development Model 1 identifies a 21% higher energy consumption due to the difference in cooling, lighting, and miscellaneous equipment. This is mainly due to the retail space's functionality and higher power intensity (W/m^2). For example, the retail portion includes a retail shop with a higher power intensity (16 W/m^2) than residential spaces such as a bedroom (13 W/m^2). The main parameters contributing to energy consumption are cooling, lighting, and miscellaneous equipment. The cooling load takes up 48% and 46% of the total energy consumption of Model 1 and Model 2, respectively, nearly half the total annual energy consumption. Meanwhile, lighting takes up 22% of the total yearly consumption in both models, and the figure is almost constant monthly. Similarly, although miscellaneous equipment makes up 15% and 18% of energy consumption in the respective models, its monthly energy demand is very stable. Other parameters, such as domestic hot water, pump, and lift, remain almost the same, making the cooling load the main contributor to the observed pattern.

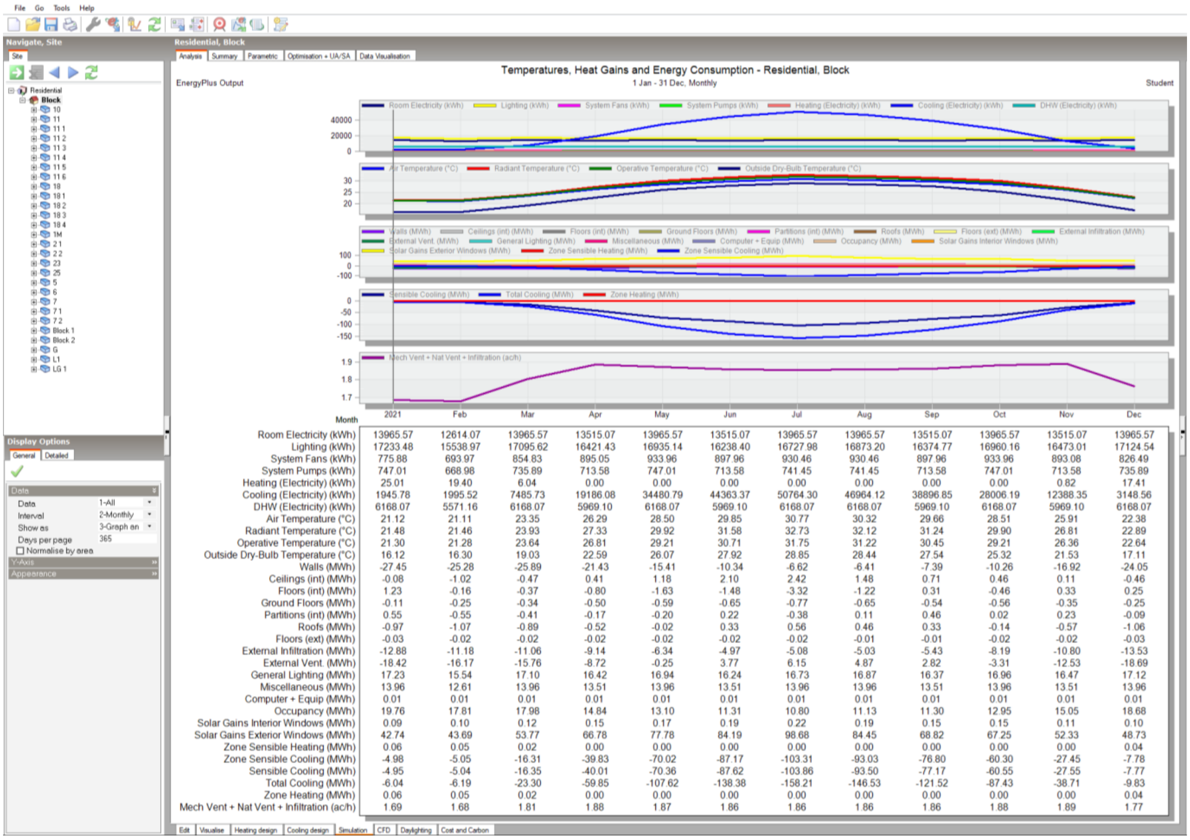


Figure 6. Energy simulation results for Model 1.

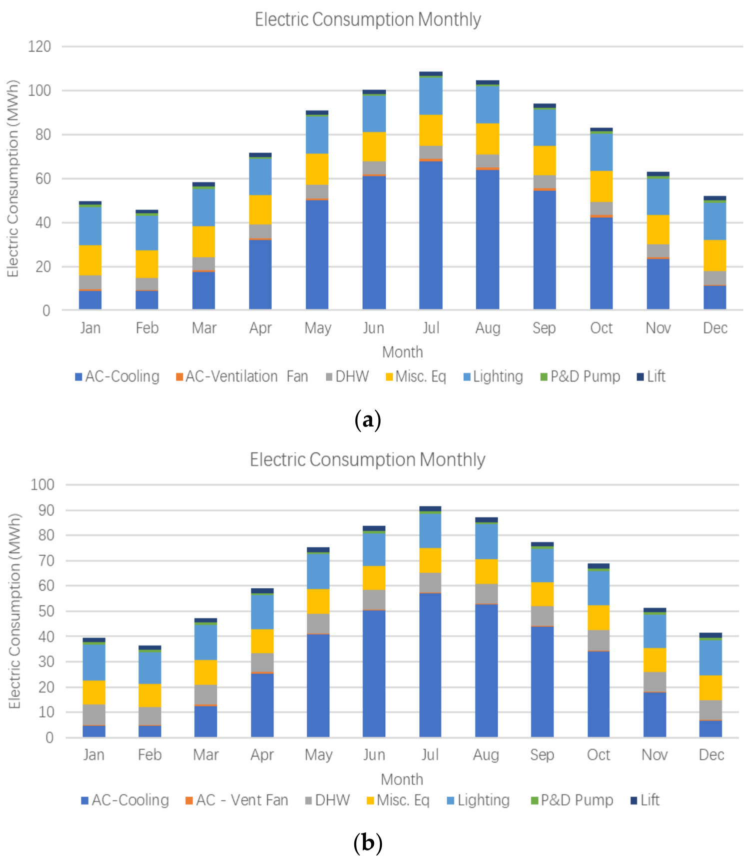


Figure 7. Monthly energy consumption for (**a**) Model 1 and (**b**) Model 2.

2.2.5. Operational Carbon Calculation Considering Climate Action Plan

Predicting the future change in emission factors impacted by the government's long-term climate-related policies is challenging. After the energy consumption is evaluated, the operational carbon of the residential building (Model 1) over its 50-year operating lifecycle can be predicted. As such, two climate scenarios are developed, assuming the difference in annual energy consumption and electricity grid emission factors.

- **1.5 °C Net-Zero World Scenario:** a world where global warming is limited to 1.5 °C through stringent climate policies, innovation, and demand-led change reaching global net-zero CO_2 emissions around 2050. This assumes that energy consumption in each decade will continue to reduce due to the technological advancement of HVAC systems. For example, the COP for HVAC will improve by around 15% per decade to meet Hong Kong's Climate Action Plan 2050 of the Hong Kong government. In addition, it is assumed under this modelled scenario that Hong Kong Electric will achieve 100% gas-fired electricity output in the next decade (by 2033). The electricity emission factor is expected to be reduced from 0.71 kg CO_2-e/kWh (2022) to 0.46 kg CO_2-e/kWh (2033), and it is assumed to further reduce with a linear progression to reach net zero in 2050 thereafter.
- **3 °C Hot House World Scenario:** a scenario that represents a world where no additional action is taken beyond the current policies that are in place. There will be insufficient technological investment in low-emission technologies and a continued reliance on carbon-intensive technologies to fuel growth. This assumes that the energy consumption level will stay unchanged after 2034 without any improvement. In addition, it is assumed under this modelled scenario that Hong Kong Electric will achieve 100% gas-fired electricity output in the next decade (by 2033). The electricity emission factor will be reduced from 0.71 kg CO_2-e/kWh (2022) to 0.46 kg CO_2-e/kWh (2033). It is assumed that the electricity emission factor will further improve and continue to drop by 15% per decade to meet the tightened HK's 2050 Climate Action Plan.

The operational carbon for the two scenarios is modelled and shown in Figure 8. Although the coefficient of performance (COP) of the air-conditioning system for the retail floors at 3.0 is higher than the upper floors of the residential units' air conditioning COP at 2.6, the cooling system in the retail floors is more efficient than the ones in the residential floors. Hence, when assuming a 15% improvement in COP per decade, energy consumption reduces significantly from 922 to 589 MWh per annum. With the improving electricity grid emission factors, the total operational carbon over 50 years is 3.22 tonnes CO_2-e/m^2. Comparatively, the operational carbon emissions under the 3 °C Hot House World Scenario are calculated as 5.53 tonne CO_2-e/m^2, without considering any improvement in HVAC COP and less ambitious improvement in the electricity grid emission factors.

Service life	50 years															
	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034-2043 (10 yr)	2044-2053 (10 yr)	2054-2063 (10 yr)	2064-2071 (8 yr)
Annual consumption (MWh)	922	922	922	922	922	922	922	922	922	922	922	922	771	701	643	589
Electricity EF (kg CO_2e/kWh)	0.71	0.71	0.71	0.67	0.67	0.67	0.56	0.56	0.56	0.46	0.46	0.46	0.31	0.15	0	0
Operational carbon (Tonne CO_2e)	655	655	655	618	618	618	516	516	516	424	424	424	2390	1052	0	0
Total carbon emissions (tonne CO_2-e)																**10,081**
Operational carbon intensity (tonne CO_2-e/m^2)																**3.22**

(**a**)

Service life	50 years															
	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034-2043 (10 yr)	2044-2053 (10 yr)	2054-2063 (10 yr)	2064-2071 (8 yr)
Annual consumption (MWh)	922	922	922	922	922	922	922	922	922	922	922	922	922	922	922	922
Electricity EF (kg CO_2e/kWh)	0.71	0.71	0.71	0.67	0.67	0.67	0.56	0.56	0.56	0.46	0.46	0.46	0.39	0.32	0.27	0.22
Operational carbon (Tonne CO_2e)	655	655	655	618	618	618	516	516	516	424	424	424	3596	2950	2489	1623
Total carbon emissions (tonne CO_2-e)																**17,297**
Operational carbon intensity (tonne CO_2-e/m^2)																**5.53**

(**b**)

Figure 8. Operational carbon prediction over the 50-year building lifecycle. (**a**) Operational carbon for 1.5 °C Net-Zero World Scenario (for Model 1). (**b**) Operational carbon for 3 °C Hot House World Scenario (for Model 1).

3. Optimisation for Lifecycle Carbon Mitigation

Table 6 shows the total carbon emissions, including the upfront embodied carbon and 50-year lifecycle operational carbon. The embodied carbon is taken from the EC calculator as 1.44 tonne CO_2-e/m^2. Operational carbon is obtained from the BIM-based energy simulation concerning the 1.5 °C Net-Zero World Scenario at 3.22 tonne CO_2-e/m^2. Provided the lifecycle carbon emissions, the variations of materials and designs for mitigating the carbon footprint are presented in the following subsections.

Table 6. Lifecycle carbon emissions for the residential building.

Scope of Carbon Calculation and Analysis	Carbon Footprint
Total embodied carbon (tonne)	4519.7
Scope (1)—Direct emissions	-
Scope (2)—Energy indirect emissions	149.7
Scope (3)—Other indirect emissions	4369.9
Embodied carbon per floor area (tonne CO_2-e/m^2)	1.44
Total operational carbon over 50 years (tonne)	10,080.6
Operational carbon per floor area (tonne CO_2-e/m^2)	3.22
Total carbon emissions (tonne CO_2-e/m^2)	4.66

3.1. Architectural Design

The reduction of carbon emissions could be achieved with changes in certain architectural or structural design features. From an energy conservation perspective, optimising the orientation of a building might help reduce the energy use of the building, as occupants would find better thermal comfort without much mechanical cooling or heating. An experiment is conducted to analyse the impact of heat gain within a building with variable building orientations. Model 1, a mix of residential and retail development, is subjected to eight orientations varied in intervals of 45 degrees and separate simulations are run to quantify the energy demand in each orientation. Given the initial Model 1 at the orientation of 135°, Model 1 is orientated to solar azimuth angles of 0°, 45°, 90°, 180°, 225°, 270°, and 315°. The annual energy consumptions for the respective orientations are compared as illustrated in Figure 9. The highest total energy consumption peaks at 967 MWh at a 45° solar azimuth angle, suggesting this orientation is the least energy efficient. On the other hand, the lowest total annual energy consumption is 893 MWh at 180°, making this the ideal orientation for Model 1 to achieve the lowest energy consumption. By designing the building with its most optimum orientation at 180°, energy savings of 29 MWh can be achieved annually, which will be crucial in saving the environment in the long run.

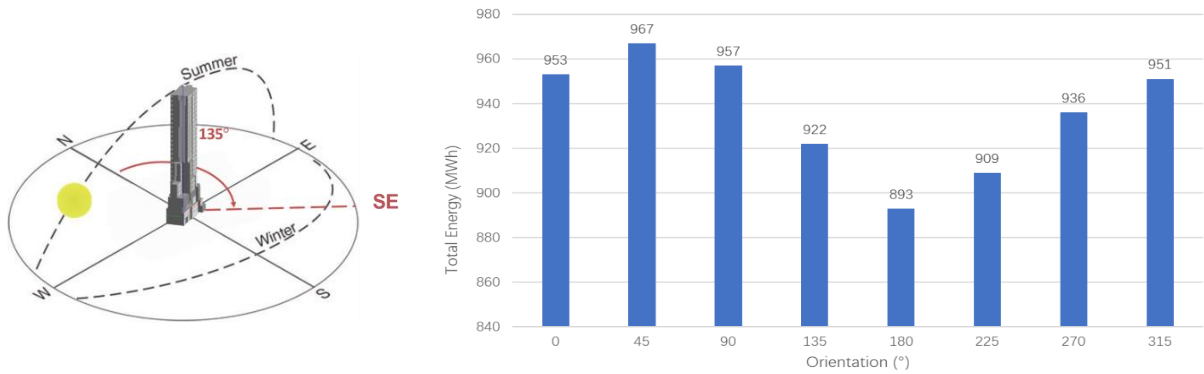


Figure 9. Total annual consumption of Model 1 in different orientations.

As shown in Figure 10, the most apparent reason for the difference in energy consumption across the different orientations is the varying demand in cooling load caused by the solar radiation transmitted into the buildings. Hong Kong, located in the globe's northern hemisphere, has the summer Sun primarily in the north of the sky, while the winter Sun is entirely in the southern sky. This positioning of the Sun is, therefore, very significant in influencing heat gain in the buildings, which makes building orientation crucial when evaluating the energy efficiency of a building. The side of buildings with the most windows and frequently used rooms should face south so that occupants receive adequate winter sunlight and minimal summer solar radiation. Therefore, when the building is at a 180° orientation, the Sun's position is ideal for buildings in Hong Kong, catching adequate solar radiation throughout the winter while preventing overheating of the building throughout the summertime. This allows maximum daylighting and decreasing heat gain, ultimately minimising energy use. It must be noted that orientation is only one of the factors for lifecycle performance optimisation, and a more balanced approach with factors of view, energy consumption, and site constraints would be recommended.

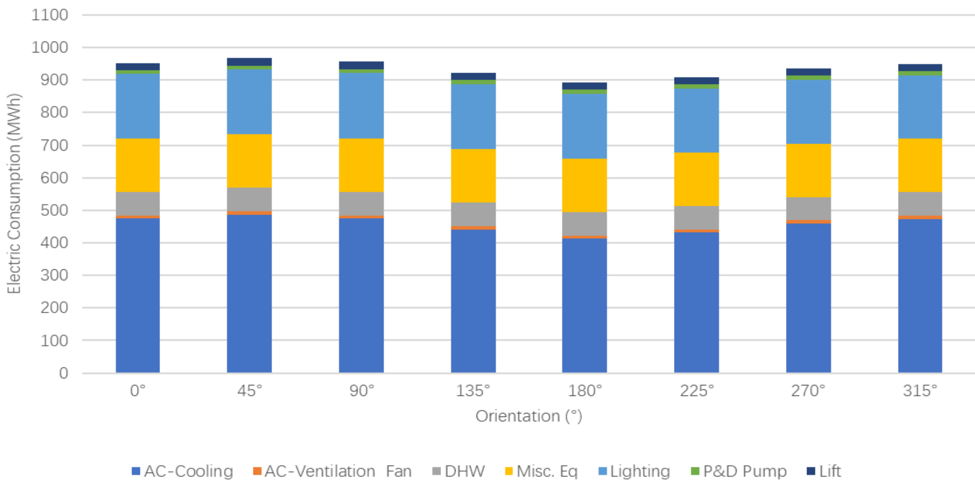


Figure 10. Annual energy consumption for Model 1 in different orientations.

3.2. Low-Carbon Construction Materials

Applying alternative materials can play a significant role in mitigating carbon emissions. This section explores material substitution and manufacturing methods which could aid in the reduction of upfront embodied carbon. These include utilising cement substitution materials such as pulverised fly ash (PFA) at 35% and ground granulated blast-furnace slag (GGBS) at 75%, as conventional cement production is a carbon-intensive process. However, for steel, the inclusion of 30% scraps through the BF-BOF production route and 100% scraps through the EAF route for manufacturing reinforcement bars could be used. Green hydrogen steel is a new emerging low-carbon material investigated in this study. Hydrogen is used in place of coke during manufacturing to directly reduce the iron ore into iron, releasing water instead of carbon dioxide.

As shown in Figure 11a, the sole impact of recycled concrete on upfront embodied carbon is the reduction of material embodied carbon by 11% and 23% for 35% PFA and 75% GGBS, respectively, compared to the existing 2–3% PFA concrete. The impact of using recycled or hydrogen steel to mitigate total material embodied carbon is much higher. While using virgin steel results in the total carbon emission of 4296 tonnes of CO_2-e, using BF-BOF steel (30% scraps) and EAF steel (100% scraps) can reduce the upfront embodied carbon by up to 10.9% and 44.4% compared to virgin steel. Furthermore, hydrogen steel can reduce carbon emissions by over 50%. The findings are supported by a study on green hydrogen-based direct reduction in the EU, which reported that the production of green hydrogen steel could result in emissions as low as 166 kgCO_2-e/tonne. This and the additional carbon emission reduction from rebar processing (160 kgCO2-e/tonne) would result in embodied carbon in the reinforcement bar as low as 326 kgCO_2-e/tonne. Combined, the effect of cement substitutes and recycled steel on the upfront embodied carbon is substantial. Figure 11c shows that the upfront embodied carbon can be reduced by approximately 21.9% and 52.2% with 35% PFA and 30% BF-BOF steel or 25% PFA and 100% EAF steel. The embodied carbon of the investigated project can be lowered by 50.2% compared to the virgin concrete and steel scenario through sole utilisation of hydrogen steel. It must be noted that these low-carbon materials mainly impact the upfront embodied carbon, which constitutes 30.90% of the lifecycle carbon emissions of residential buildings. The actual impact on carbon emissions of the entire building needs to factor in the proportion of upfront embodied carbon, which might slightly vary amongst different building design options.

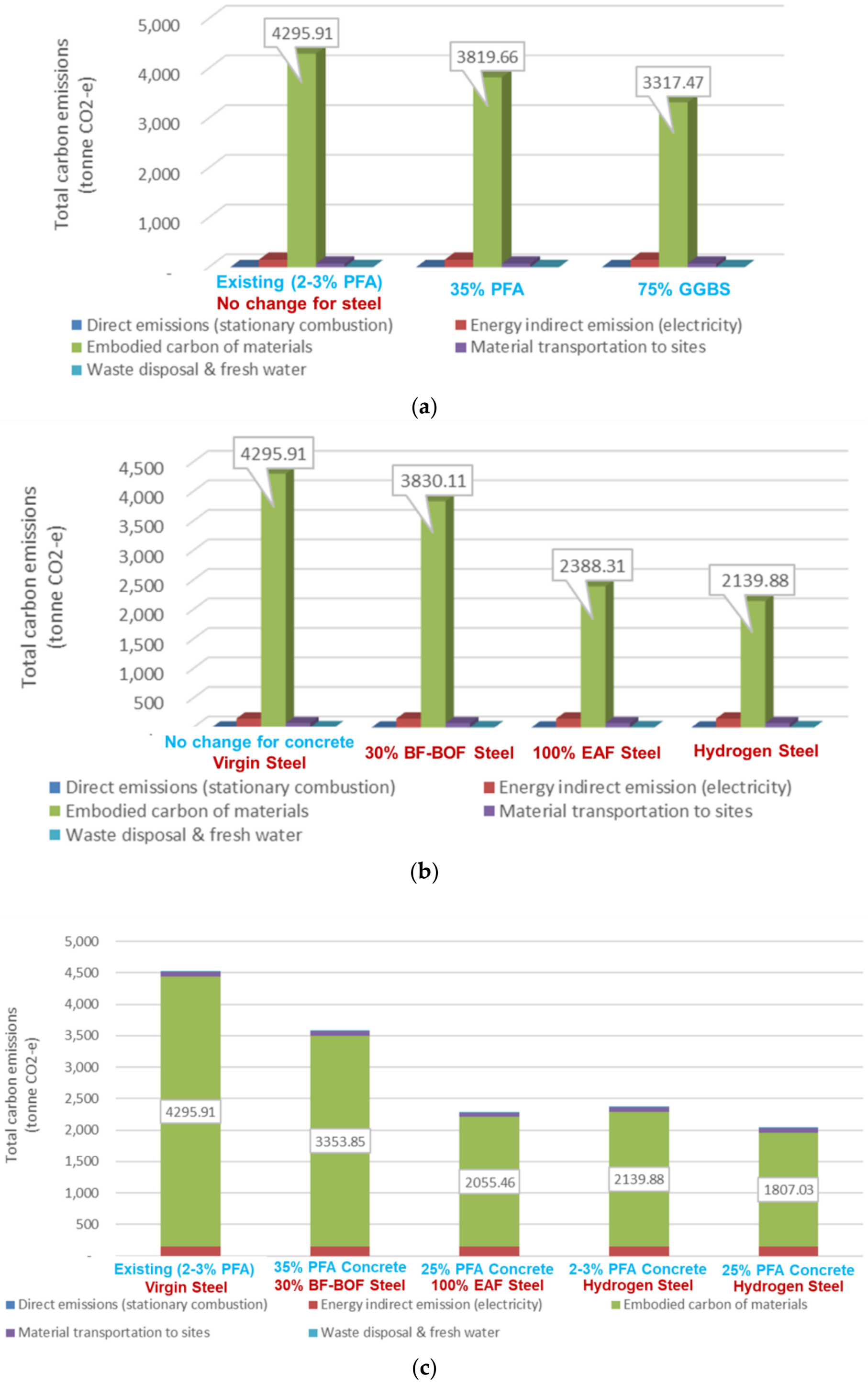


Figure 11. Impacts of cement substitutes, steel scraps, and green hydrogen steel. (**a**) Impact of cement substitutes on upfront embodied carbon. (**b**) Impact of steel scraps and green hydrogen steel on upfront embodied carbon. (**c**) Impact of combined use of low-carbon materials on upfront embodied carbon.

3.3. Modular Integrated Construction and DfMA

Other novel construction approaches, such as modular integrated construction (MiC), are explored to identify improvement opportunities for future residential development projects. The existing building uses reinforced concrete (RC), and an alternative modularisation of the floor layout is proposed. Figure 12 compares the existing RC and the proposed MiC layout. This involves first identifying the functionality of the spaces, followed by breakdown of the identified spaces into standard dimensions according to allowable limits for MiC (i.e., height limit: 4.5 m, width limit: 3.4 m, length limit: 12–14 m). No modification to the structural system is made to minimise the impact of modularisation on structural stability. Table 7 demonstrates the change in concrete applications and embodied carbon emissions. Change in MiC only results in a 1.88% reduction in carbon emissions. The carbon reduction is minimal because MiC conversion is highly limited due to the restriction/constraint on space utilisation, structural considerations, and functionality requirements. The modelled carbon reduction is mainly attributed to the redistribution of indoor spaces with volumetric modules.

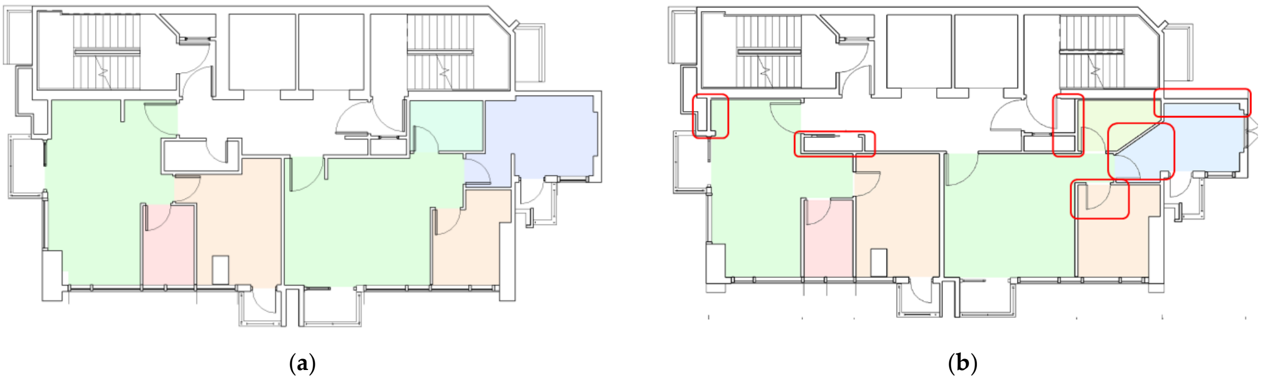


Figure 12. Comparison of layout plans using (**a**) RC and (**b**) MiC. (**a**) Typical layout for original Model 1. (**b**) Proposed MiC layout based on BIM.

Table 7. Comparison of embodied carbon for RC and MiC.

	RC	MiC
The volume of concrete (m^3)	1967.4	1945.2
Emission factor (kg CO_2-e/m^3)	394 (Grade 60) [a]	391 (Precast concrete) [b]
Carbon emissions for main concrete applications (kg CO_2-e)	775,155.6	760,573.2

[a] Emission factor for concrete. [b] Adopted from [51].

An alternative construction method is DfMA, which refers to the design of prefabricated components or volumetric modules for factory-based production. MiC partially overlaps the concept of DfMA. In this study, the impact of DfMA on the embodied carbon is also minimal because structural components of the studied residential project need to remain unchanged due to the structural requirements. Subject to building regulatory and functionality considerations (such as sound insulation), the size of existing partition walls (75–100 mm, etc.) cannot be further minimised using precast concrete panels. Precisely, the typical size of lightweight precast wall panels (inner) is 100 mm, close to the size of the existing partition walls. However, the literature has indicated that adopting MiC/DfMA at the early design stage has a large potential to mitigate carbon emissions. It is suggested to factor in DfMA (either MiC or prefab parts) at the early project development stage to optimise the space organisation and structural form for maximising the upfront embodied carbon reduction.

4. Conclusions

This study describes the calculation of upfront carbon emissions and modelling supported by BIM to assess the lifecycle energy and carbon performance and demonstrates the significance in promoting the lifecycle-oriented design of green buildings. Formulas for measuring upfront embodied carbon are proposed, considering the cradle-to-site emissions related to material manufacturing, transportation, on-site construction activities, and waste disposal and treatment. This study is designed to examine the potential of energy conservation and carbon reduction and its influential factors for different utilisations of buildings through BIM-enabled parametric modelling. By improving the interoperability of BIM and energy simulation, the new parametric method promotes the accuracy of data modelling and, through the process, partially resolves compatibility problems between the two platforms. BIM-based energy simulation is also conducted to examine the potential of energy conservation and its influential factors in residential buildings. The results of various optimisation strategies for carbon mitigation offer more significant insights into the environmental performance of residential buildings using alternative materials and designs. The methodology used in this study is adaptable to other building types and their various uses, which can add to the body of knowledge on energy savings.

However, a few limitations still require further exploration through future research. While the present study is conducted using locally specific emission factors, there is the possibility to generalise the formulation and emission factors for evaluating the lifecycle sustainability performance. In addition, the energy simulation has some difficulty processing large and complex models. To facilitate the simulation process, the model has been simplified, such as by combining small windows into an extensive panel to reduce the number of elements in the model significantly. With many of such elements amended in the BIM model, the accuracy of the data obtained may be slightly affected. In addition, with a broad spectrum of factors affecting a building's energy consumption, more extensive research can be carried out on other parameters and factors in terms of practical considerations that might affect a building's energy consumption. This could include the control decisions, actual heating and ventilation loads, and even the occupant's socioeconomic characteristics in the actual use of the building. By conducting a more comprehensive and critical analysis of these factors in future, meaningful findings could be found that could be used as part of energy and carbon reduction strategies for future buildings.

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