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Developing a BIM-Based Methodology Framework for Sustainability Analysis of Low Carbon High-Rise Buildings

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Abstract: In high-density high-rise cities such as Hong Kong, buildings account for nearly 90% of energy consumption and 61% of carbon emissions. Therefore, it is important to study the design of buildings, especially high-rise buildings, to achieve lower carbon emissions in the city. The carbon emissions of a building consist of embodied carbon from the production of construction materials and operational carbon from energy consumption during daily operation (e.g., air-conditioning and lighting). An integrated analysis of both types of carbon emissions can strengthen the design of low carbon buildings, but most of the previous studies concentrated mainly on either embodied or operational carbon. Therefore, the primary objective of this study is to develop a holistic methodology framework considering both embodied and operational carbon, in order to enhance the sustainable design of low carbon high-rise buildings. The framework will be based on the building information modeling (BIM) technology because BIM can be integrated with simulation systems and digital models of different disciplines, thereby enabling a holistic design and assessment of low carbon buildings. Structural analysis program is first coupled with BIM to validate the structural performance of a building design. The amounts of construction materials and embodied carbon are then quantified by a BIM-based program using the Dynamo programming interface. Operational carbon is quantified by energy simulation software based on the green building extensible Markup Language (gbXML) file from BIM. Computational fluid dynamics (CFD) will be applied to analyze the ambient wind effect on indoor temperature and operational carbon. The BIM-based framework serves as a decision support tool to compare and explore more environmentally-sustainable design options to help reduce the carbon emissions in buildings.

Key words: building information modeling, energy simulation, low carbon building, wind-driven ventilation, structural analysis

1. INTRODUCTION

Global warming is considered one of the most important and urgent environmental issues facing mankind. Among various sources of anthropogenic greenhouse gas (GHG) emissions, the building sector is the biggest contributor, representing 40% of the world's energy consumption and around one third of global GHG emissions [1]. For high-density high-rise cities such as Hong Kong, the building sector even accounts for 90% of total electricity consumption and 61% of total carbon emissions in the city [2]. Therefore, it is important to study and reduce the energy consumption and carbon emissions from buildings, especially high-rise buildings.

The concept of low carbon buildings has become an important strategy to achieve energy conservation and carbon reduction in buildings. For example, studies by the U.S. Department of Energy showed that low carbon green buildings consume 25% less energy and generate 34% lower carbon emissions [3]. Kofoworola and Gheewala [4] investigated the carbon emissions from different life cycle stages of a 38-story office building, including material production, construction, operation and demolition. It was found that building carbon emissions are mainly associated with two life cycle stages: around 40% is emitted from the material production (known as embodied carbon) and 56% is emitted during building operation (often referred to as operational carbon) [4]. Due to their significant impacts, previous studies have mainly focused on the embodied carbon or operational carbon associated with different design alternatives in order to find low carbon options. Junnila and Horvath [5] applied environmental life cycle assessment (LCA) to estimate the embodied carbon from production of various materials in an reinforced concrete (RC) building. The study showed that concrete and rebar accounted for around 90% of the embodied carbon in an RC building. Gong [6] compared the embodied carbon of a 3-storey residential building constructed from different materials, such as RC, steel and wood. The results of the study indicated that a wood frame and a steel frame generated lower embodied carbon (by 44% and 49%) than an RC frame. Alternatively, Gan et al. [7] estimated the embodied carbon of high-rise RC and steel buildings associated with different structural forms and building heights, a result that can help structural engineers determine low carbon structural forms at the early stage of building design.

Operational carbon is related to the consumption of energy by different indoor facilities such as lighting, heating, ventilation and air-conditioning (HVAC) during building operation [8]. Energy simulation of a building can be performed to anticipate the energy use of a building. Bojic et al. [9] applied an HTB2 energy model to quantify the influence of envelop and partition characteristics on the space cooling load of high-rise residential buildings in Hong Kong. The influences of solar radiation and different types of window glazing on building energy performance were also evaluated [10]. Gao and Lee [11] used computational fluid dynamics (CFD) to evaluate the influence of opening location (e.g., windows and doors) on natural ventilation and energy efficiency of residential buildings.

Many previous studies only focused on low-rise buildings and overlooked the sustainability analysis of high-rise buildings. High-rise buildings are subjected to significant wind pressures which result in adequate natural ventilation [11, 12, 13]. The wind-driven natural ventilation impacts the indoor thermal environment and the operational carbon from the consumption of energy by HVAC. In addition, the wind pressures cause considerable lateral loads at the external surfaces of a high-rise building. A previous study has shown that the lateral loads not only influence the structural performance of a high-rise building, but also impact the amounts of construction materials and embodied carbon [14]. Although some researchers [4, 9, 11, 15] have focused the analysis of high-rise buildings, these efforts only focused on embodied or operational carbon and did not consider an integrated analysis of both parts.

An integrated analysis of embodied and operational carbon in high-rise buildings requires a high level of interoperability among different disciplines including fluid dynamics, energy simulation, structural analysis and construction materials. Building information modelling (BIM) provides a data exchange framework that can improve the interoperability among engineering analyses of different disciplines, and therefore opens up a new way to analyze the carbon emissions in high-rise buildings. For example, Stadel et al. [16] presented a conceptual framework that integrates BIM and energy simulation software in order to estimate the operational energy consumption and carbon emissions from different indoor facilities. Similarly, Schlueter and Thesseling [17] applied a BIM-based energy assessment tool to the early design stage for the instantaneous evaluation of operational energy consumption. Some researchers have also studied the use of BIM to quantify the embodied carbon of various construction materials in buildings [18, 19]. However, these studies focused on embodied or operational carbon and did not consider the wind effect or structural performance perspective.

The objective of this paper is to develop a BIM-based methodology framework that incorporates CFD (wind effect), energy simulation, structural analysis, and material embodied carbon quantification, in order to provide an integrated analysis of the embodied and operational carbon in high-rise buildings. The proposed methodology framework can extract component and material information from digital BIM models, and link the information to other software programs. Engineering analyses of different disciplines can then be conducted to evaluate and minimize the embodied and operational carbon in high-rise buildings. The findings of this research would be of significant value to the design of low carbon high-rise buildings, thereby helping construct sustainable low carbon cities.

2. METHODOLOGY

This section presents a BIM-based methodology framework for quantifying and analyzing the embodied and operational carbon in high-rise buildings. This study considers three types of GHG, which are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), because they account for over 95% among various GHG emissions [20]. The emissions of CO_2, CH_4, and N_2O are converted to carbon dioxide equivalent (CO_2-e) by multiplying each GHG emission with their global warming potential (GWP) values, which are 1, 25, and 298, respectively [21]. The final results are presented in terms of kilogram CO_2-e per metre square floor area. As shown in Fig. 1, the proposed methodology framework includes four major steps: (1) creation of the design BIM model, (2) embodied carbon quantification, (3) operational carbon quantification, and (4) scenario study and identification for design improvement.

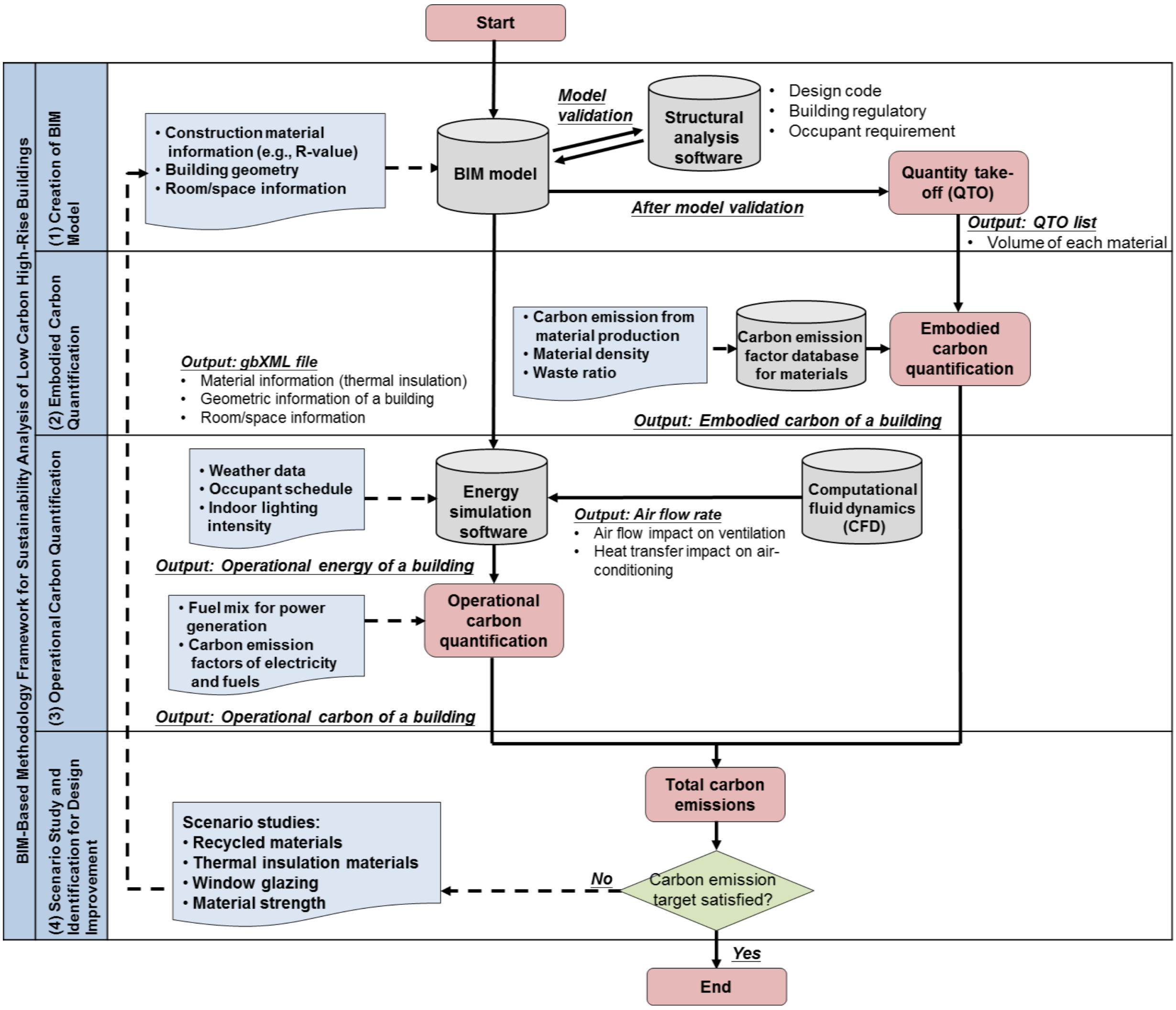


Fig. 1. Proposed BIM-based methodology framework for sustainability analysis of high-rise buildings

2.1. Creation of design BIM model

The methodology framework begins with creating a design BIM model, which is composed of building geometry, types of components, dimensions, etc. for a building. The BIM model contains structural components (such as shear walls, columns and beams) and non-structural components (like windows and doors). Each building component is specified by its construction materials as well as the thermal (e.g., thermal conductivity) and mechanical properties (e.g., strength, elastic modulus). For example, shear walls are often constructed from reinforced concrete while windows contain aluminum frames and glasses. In addition to the geometric and material information, all of the rooms in a design BIM model should be defined by space boundaries for the identification of different air-conditioned zones in energy simulation. Generally, a complete building BIM model should contain geometric, material and space information, which is used to quantify embodied carbon and operational carbon. It should be noted that design BIM models may not have some construction materials and methods details, such as the thermal insulation layers. These materials and methods details will be defined in specific engineering analysis programs (e.g., energy simulation) to incorporate their impacts on carbon emissions quantification. Structural analysis software (i.e., ETABS) is applied to check with the design code and validate the structural performance of the design BIM model (e.g., building total drift, inter-story drift, and component strength), thereby reducing any concerns on the building structural behavior. After BIM model checking, the geometric, material and space information contained in the BIM model is extracted and used to quantify embodied and operational carbon.

2.2. Embodied carbon quantification

Embodied carbon is emitted during the manufacturing and transportation of construction materials including structural materials (e.g., concrete and steel rebar) and non-structural materials (e.g., thermal insulation and window glazing). Embodied carbon of a building is quantified by multiplying the amount of construction materials with their corresponding embodied carbon emission factors. The embodied carbon emission factor of a material covers all relevant production processes (e.g., resource extraction and manufacturing) and transportation to construction sites. Below is the formula for calculating the embodied carbon as adopted from [22]:

$$EC = \sum_{j=1}^{J} \left[\sum_{i=1}^{I} Q_{ij} EF_{ij} + \sum_{i=1}^{I} \sum_{l=1}^{L} Q_{ij} D_{il} EF_l \right] A^{-1} \tag{1}$$

where i refers to a sourcing location, j is a construction material, l stands for the means of transport by which the material is delivered to the construction site. Q_{ij} is the quantity of material j obtained from location i. Q_{ij} can be calculated, given the material and geometric information of each building component from BIM. EF_{ij} represents the carbon emissions for the production of material j obtained from location i. D_{il} refers to the total transportation distance from location i to the construction site by transportation method l, EF_l stands for the emission factor for transportation method l. Heavy-weight vehicles are often used to deliver construction materials, with an emission factor of 0.033 kg CO_2-e/tonne/km [23]. A is the gross floor area of a high-rise building.

It is tedious to manually calculate the quantities of construction materials used in a high-rise residential building, as each floor has different component layouts and member sizes. Therefore, the Dynamo visual programming interface is used to create a computer-aided quantity take-off (QTO) tool. As shown in Fig. 2, material and geometric information of each BIM building component is automatically extracted as the inputs to calculate the material quantity Q_{ij}. The material quantity information obtained from the QTO tool is linked with an embodied carbon emission factor database to automatically calculate the embodied carbon in a high-rise building. This study focuses on the primary structural (e.g., rebar and concrete) and non-structural materials (e.g., window and door) used in construction, while the finishing, temporary (e.g., formwork) and waste materials are not considered.

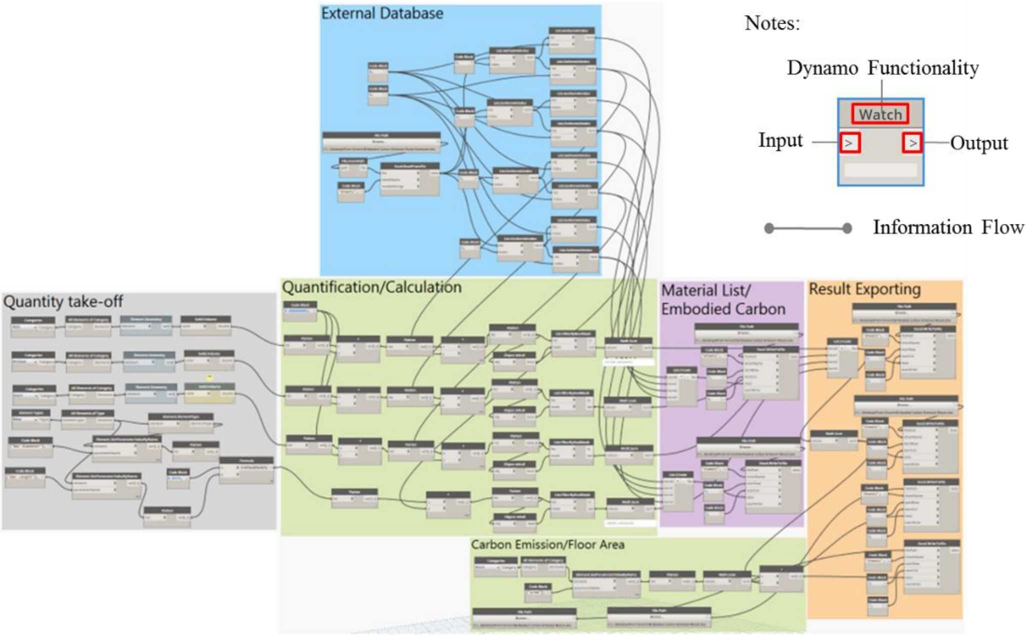
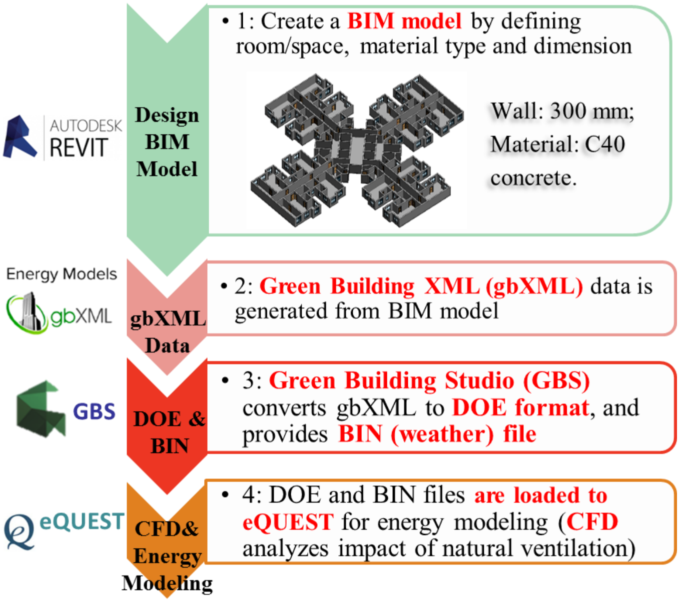


Fig. 2. Computer-aided QTO tool using Dynamo visual programing interface

2.3. Operational carbon quantification

Operational carbon refers to carbon emissions from energy-consuming facilities such as lighting and HVAC during building operational. Energy consumption during building operation can be assessed using energy simulation software, considering the building configuration, space use type (e.g., bedroom or living room) and material thermal insulation (e.g., thermal conductivity) which can be obtained from BIM. Fig. 3 shows the procedures of energy simulation.



- 1: Create a **BIM model** by defining room/space, material type and dimension
- 2: **Green Building XML (gbXML)** data is generated from BIM model
- 3: **Green Building Studio (GBS)** converts gbXML to **DOE format**, and provides **BIN (weather) file**
- 4: DOE and BIN files **are loaded to eQUEST** for energy modeling (**CFD** analyzes impact of natural ventilation)

Fig. 3. Procedures for energy simulation

Operational energy consumption during the entire lifespan of a building is quantified by energy simulation software (i.e., eQUEST) based on the green building extensible Markup Language (gbXML) file from BIM. The building configuration, defined space boundary and material thermal insulation property obtained from BIM are used for estimating the operational energy consumption. Weather file, occupant schedule, indoor lighting and equipment intensities are determined in energy simulation software to calculate the total cooling load. CFD program can be used to analyze the wind-driven natural ventilation on the indoor thermal environment and operational energy consumption of a high-rise building. The operational energy consumption is converted into operational carbon by multiplying with the emission factor of specific energy type, as follows:

$$OC = [EU \times EF_e \times L]A^{-1} \tag{2}$$

where EU refers to annual operating energy use for the building. EF_e represents the emission factor for the energy type e, and the value for electricity is 0.58 kg CO_2-e/kWh [24]. L is the service life of the building, in which L = 50 years in this study. A is the gross floor area of a high-rise building. Because embodied and operational carbon already accounts for over 95% of the building life cycle emissions, the carbon emissions from building demolition and waste disposal are not included [4].

2.4. Scenario study and identification for design improvement

The summation of embodied and operational carbon gives the total carbon emissions of a high-rise building. Different design options can be studied using the proposed framework in order to identify the least carbon option. For example, one may use construction materials with better thermal insulation, thus reducing operational energy and carbon, but the materials may contain higher embodied carbon due to their compositions and production methods. Therefore, the trade-off impact of using materials of different sources and thermal properties on the embodied and operational carbon of high-rise buildings can be studied using the proposed methodology framework. The configurations of the design BIM model (e.g., material strength, floor plan, and building orientation) need to be changed, followed by the quantification of embodied carbon (Section 3.2) and operational carbon (Section 3.3). The procedures will be examined several times to evaluate different design options. The results will be compared for identifying design and building performance improvement.

3. ILLUSTRATIVE EXAMPLE

A typical 40-story (108 m) high-rise residential building in Hong Kong is selected for applying the framework proposed in this paper. As shown in Fig. 4, each story has 959 m^2 and the floor plan contains 20 flats, including four one-person flats, eight two-person flats, four three-person flats, and four three/four-person flats. The flats are connected by corridors with stairs and elevators on the middle of the building. The building is an RC shear wall structure. The shear walls are 300 mm thick, constructed from C40 concrete and 460 MPa high-strength rebar. In addition, the non-structural components include 200 mm partition walls using 10 MPa low-strength block, wooden doors and 6 mm clear float glass windows.

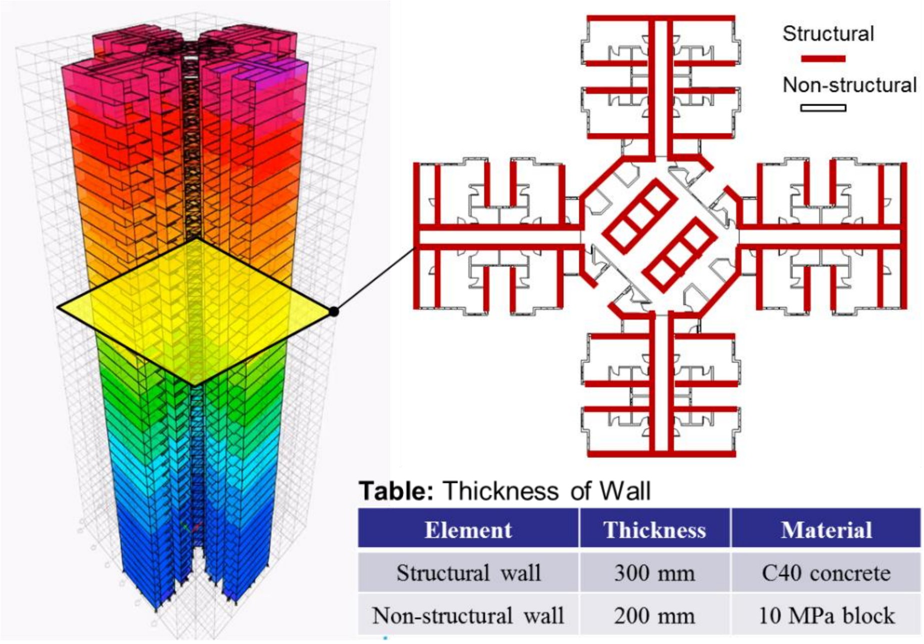


Table: Thickness of Wall

Element	Thickness	Material
Structural wall	300 mm	C40 concrete
Non-structural wall	200 mm	10 MPa block

Fig. 4 Overview of the 40-story high-rise residential building

Table 1 summarizes the embodied carbon emission factors for different materials. The building model created in BIM is exported to structural analysis software (i.e., ETABS) for structural performance validation. The wind load used in structural analysis is estimated according to the Code of Practice on Wind Effects in Hong Kong [25]. The results indicate that the BIM model satisfies the maximum lateral displacement criteria (H/500), in which H is the total building height.

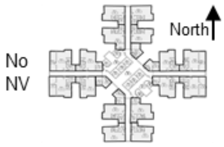
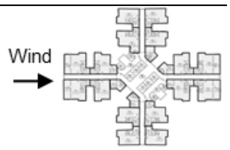
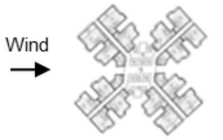
Table 1 Embodied carbon emission factors for structural and non-structural materials

Material	Per-unit embodied carbon	Unit	Density (kg/m^3)	Data source
Rebar	2.25	kg CO_2-e/kg	7700	[22]
C40 Concrete	335	kg CO_2-e/m^3	2400	[22]
10 MPa Block	0.078	kg CO_2-e/kg	2400	[26]
Glass	1.2	kg CO_2-e/kg	2500	[26]
Wood	0.45	kg CO_2-e/kg	600	[26]
Polystyrene	2.54	kg CO_2-e/kg	25	[26]

After the model is validated, the material and geometric information from BIM is taken to calculate the quantities of materials, using the Dynamo-based QTO tool. Following Eq. (1), the material quantities are multiplied with carbon emission factors to calculate the embodied carbon in the building. On the other hand, the BIM model exports the building configuration and space boundary to eQUEST for energy simulation. Given the hot summer weather of Hong Kong, air-conditioning (i.e., fan and space cooling) contributes a large proportion of the electricity consumption in buildings, thus this study mainly focuses on air-conditioning. The main cooling seasons are from April to November and the threshold for turning on cooling is 28 ^{o}C with reference to [13]. The outdoor temperature ranges from 22 to 29 ^{o}C (from HK Observatory) over the cooling seasons (with a mean of 26 ^{o}C). The air-conditioned zones include bedrooms, living and dining rooms while other zones (e.g., toilets) do not have air-conditioning. The external walls are insulated by 50 mm Polystyrene (thermal conductivity = 0.034 W/m/K). The thickness and thermal conductivity for other materials (e.g., concrete and glass) are also determined in eQUEST.

High-rise buildings are subjected to significant wind pressures that result in strong natural ventilation airflow. If windows are opened and most of the flats in the building could be naturally ventilated, then the use of air-conditioning and the operational energy consumption could be reduced. This study compares scenarios with or without natural ventilation (see Table 2). In Scenario 1, the windows are closed all the time, and building occupants rely on air-conditioning for fresh air supply and space cooling. As such, the fans of air-conditioners need to operate 24 hours of a day for fresh air supply while cooling function is only active when indoor temperature exceeds the threshold 28 ^{o}C.

Table 2 Summary of scenarios for the 40-story building with/without natural ventilation

Scenario	Natural ventilation	Operation of air-conditioner	Building orientation	
1	No (windows close all the time)	Turn on air-conditioner: (1) Fan operates 24 hours for fresh air supply; (2) Cooling is NOT active if $T_{indoor} < 28$ ^{o}C; (3) Cooling is active if $T_{indoor} > 28$ ^{o}C.	0^{o}	
2	Yes (windows open if $T_{indoor} < 28$ ^{o}C)	If $T_{indoor} > 28$ ^{o}C (e.g., overheat due to solar radiation), close windows and turn on air-conditioner: (1) Fan operates for fresh air supply (2) Cooling is active to control T_{indoor}	0^{o}	
3			45^{o}	

Note: The initial and controlled indoor temperature (after turning on cooling) is 25 ^{o}C.

In Scenarios 2 and 3, all windows are open in the initial state. Given the surrounding wind profile, ANSYS Fluent is utilized to study the wind pressures at various windows on the building and predict natural ventilation airflow (m^3/s) driven by the pressure difference throughout each flat. The computational domain used in this study is 5H height ×10H width × 20H length (H is the building height). One velocity inlet is considered using the typical Hong Kong wind profile with the power law exponent $\alpha = 0.15$. The natural ventilation airflow for each flat obtained from ANSYS is used in eQUEST to calculate the space heat gain/loss and the operational energy consumption. If the outdoor temperature is lower than the indoor temperature, the natural ventilation airflow potentially cools the flats and saves the energy consumption for air-conditioning. At certain times (e.g., at noon), some flats may overheat due to strong solar radiation and the indoor temperature may exceed 28 °C. In such cases, the windows should be closed while turning on air-conditioners for fresh air and cooling. The building energy consumption over 50 years is predicted and converted to operational carbon by Eq. (2).

4. RESULTS AND DISCUSSION

Fig. 5 shows the embodied carbon of construction materials and operational carbon from air-conditioning. The results indicate that Scenario 1 has the most carbon emissions at 837 kg CO_2-e/m^2. If the building occupants can open the windows and utilize natural ventilation (such as in Scenario 2), the carbon emissions of the building can be reduced by around 30% to 605 kg CO_2-e/m^2. It implies that utilizing natural ventilation can provide enough fresh air and help maintain a comfortable indoor temperature, thereby reducing the air-conditioning energy consumption.

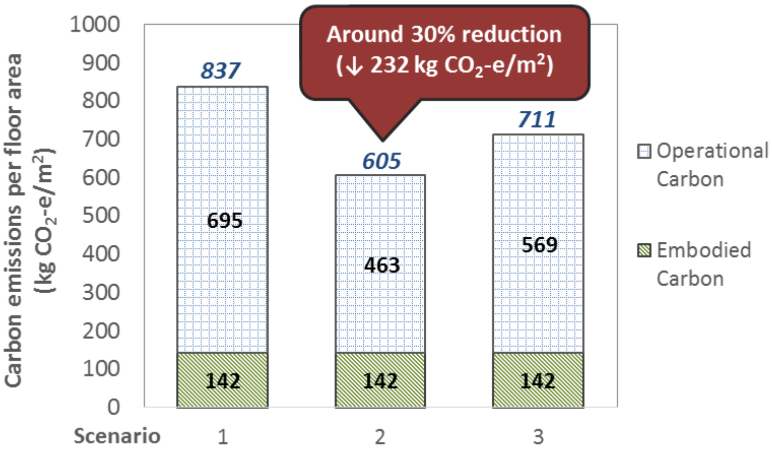


Fig. 5. Embodied carbon of construction materials and operational carbon from air-conditioning

Fig. 6 (a) shows the airflow velocity distribution for Scenario 2 obtained from ANSYS Fluent. Windward walls have positive static wind pressures that result in infiltration type natural ventilation. The natural ventilation airflow (m^3/s) is high on the windward walls and air change per hour (ACH) is more than 30. This provides a large potential to reduce the indoor temperature and save the air-conditioning energy consumption. Leeward walls have negative static wind pressures and suction type natural ventilation. The airflow on the leeward walls is much smaller and the ACH for each flat is only from 5 to 20 which may not be enough to reduce the indoor temperature, especially in the afternoon when flats overheat by solar radiation. Therefore, flats on the leeward side require more AC operation to control the indoor temperature. The results also indicate that the infiltration type natural ventilation on the windward side is more efficient than the suction type ventilation on the leeward side, thereby saving more operational energy and carbon for air-conditioning.

The airflow velocity distribution for the 40-story building with 45° orientation (Scenario 3) is shown in Fig. 6 (b). The leeward walls in Scenario 3 have a larger region of turbulent than that in Scenario 2. Due to this reason, more flats on the leeward walls are subjected to negative static pressures with less efficient natural ventilation and lower ACH. As a result, the energy consumption and operational carbon of the building in Scenario 3 is 19% more than that in Scenario 2 (see Fig. 5). According to the simulation results, the Scenario 2 has the smallest carbon emissions and should be encouraged in practice. It should also be noted that the CFD and energy simulation results are based on wind speed at 40-story height. If lower building heights or wind pressures are considered, the energy and carbon reduction efficiency may be reduced.

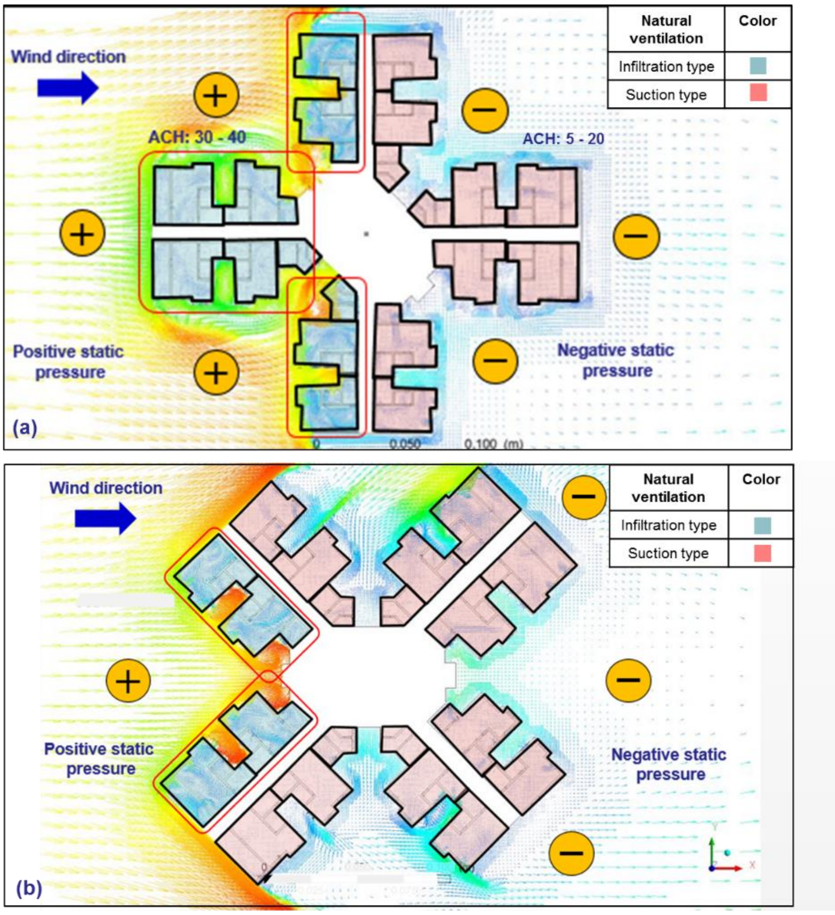


Fig. 6. Airflow velocity distribution for the building in Scenario 2 (a) and Scenario 3 (b)

5. CONCLUSIONS

This paper presents a BIM-based methodology framework for the integrated evaluation and analysis of embodied carbon and operational carbon in high-rise buildings. The proposed methodology framework starts from extracting and linking the component and material information from BIM to CFD, energy simulation, structural analysis and embodied carbon database respectively, in order to analyze the building embodied and operational carbon. An illustrative example is used to demonstrate the proposed framework. The methodology framework is generic and other engineering analyses (such as human comfort analysis) can be incorporated to enrich its functionality. The findings of this research would benefit the design of low carbon high-rise buildings, thereby helping reduce carbon emissions and construct low carbon sustainable cities. However, there are still certain limitations. First, the proposed framework does not follow the rule for bill of quantity (BOQ) rules in embodied carbon quantification. Moreover, current BIM software has interoperability issues with regards to energy simulation software, and space and thermal information may be lost during model conversion. Therefore, a schematic framework for seamless conversion between BIM models and the analytical models supported by energy simulation software is needed in future studies.

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