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Developing an automated BIM-based life cycle assessment approach for modularly designed high-rise buildings

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ABSTRACT

Modular construction has attracted increasing attention due to its energy and environmental benefits. Digital technologies such as building information modelling (BIM) have also been explored to generate and manage data through the lifecycle of buildings. Although research has been performed in the area of integrating BIM and modular construction, BIM-based automated lifecycle assessment (LCA) of prefabricated buildings remains unexplored. This study therefore aims to develop a BIM-based LCA method for prefabricated buildings incorporating different assessment levels with unique system boundaries and functional units. The developed approach can support automated assessments through all lifecycle phases of a prefabricated building. It is achieved through an automated process of creating parameters to merge LCA data into the building model, systematic zoning, model setup and impact estimation. This approach is applied to evaluate the energy and environmental performances of a case building in Hong Kong. The case study validated the efficiency of the developed BIM-based LCA method in providing a systematic and detailed assessment of modularly designed buildings. This study extends the knowledge in automated BIM-based LCA by addressing specific characteristics of prefabrication and promotes the incorporation of comprehensive and detailed LCA data into BIM models for improved design robustness and holistic performances of buildings. This validated approach will enhance the willingness of designers to apply LCA during the design stages for minimizing the energy and environmental impacts of both new and renovated buildings with prefabrication.

Keywords: *Life cycle assessment; Building information modelling (BIM); Cumulative energy demand; Global warming potential.*

Highlights

A BIM-based LCA methodology for modularly designed high-rise buildings is developed

LCA is streamlined at unique assessment levels, boundaries and functional units

Developed method is tested on a prefabricated high-rise building in Hong Kong

Approach is efficient to automate lifecycle impact assessment

Nomenclature

Acronyms

1B	1-bedroom flat
2B	2-bedroom flat
2P3P	2-person-3-person flat
ADP-f	Abiotic Depletion (kg Sb-eq)
AP	Acidification Potential (kg SO2-eq)
BIM	Building Information Modelling
BOQ	Bill of Quantity
CED	Cumulative Energy Demands
EP	Eutrophication Potential (kg PO4-eq)
FAETP	Fresh Water Aquatic ecotoxicity (kg 14-DB-eq)
GFA	Gross Floor Area
GWP	Global Warming potential (kg CO2-eq)
HA	Housing Authority
HKBD	Hong Kong Buildings Department
HTP	Human Toxicity Potential (kg 14-DB-eq)
ISO	International Organization for Standardization
LCA	Lifecycle Assessment
LCI	Lifecycle Inventory
LCIA	Lifecycle Impact Assessment
MAEP	Marine Aquatic Ecotoxicity (kg 14-DB-eq)
MiC	Modular Integrated Construction
ODP	Ozone Layer Depletion (kg CFC-11-eq)
POCP	Photochemical Oxidation (kg C2H2)
SQL	Structured Query Language
TETP	Terrestrial Ecotoxicity (kg 14-DB-eq)

List of symbols

e	energy type
E_{ee}	impact coefficient of the material
EP	total lifecycle impacts
$E_{p.e}$	mass of energy used by equipment type
EP_c	embodied impact of construction
EP_e	embodied impact of end-of-life phase
EP_m	embodied impacts of material production
EP_{mc}	embodied impacts from production of insitu elements
EP_{mp}	embodied impacts from production precast elements
EP_{mp1}	embodied impacts from materials extraction for precast elements
EP_{mp2}	embodied impacts from materials transport to prefabrication factory
EP_{mp3}	embodied impacts from manufacturing of precast elements
EP_t	embodied impacts of transportation
EP_u	embodied impact of use phase
E_{re}	impacts incurred in demolishing process
E_t	impacts from transporting materials landfills or recycling plant
f	total number of energy types
g	total number of materials to be demolished

IC	impact coefficient
IC_p	impact coefficient of material
$IC_{p.e}$	impact coefficient of energy type
IC_t	impact coefficient for transport mode
l	equipment/activity
l_f	load factor
m	the total number of precast components to be transported
n	number of different materials
p	transport mode
Q	activity quantity
q	equipment type
Q_{bo}	quantity of equipment/activity
Q_c	amount of work
Q_p	quantity of materials
$Q_{p.c}$	production volume of prefabricated component
Q_r	percentage of total materials to be recycled or landfilled
Q_t	quantity of materials to be transported
R_f	replacement factor
u	total number of activities in operation phase
w	work type to be accomplished
wf	waste factor
x	total number of transport mode
y	total number materials/components
z	total number of equipment

1. Introduction

The construction industry is a major source of environmental issues since buildings contribute 39% of the annual global carbon emissions due to the production of construction materials and direct or indirect energy use during the operation phase (Khoshnava et al., 2018; Radhi and Sharples, 2013). In high-density cities like Hong Kong, buildings account for 90% of carbon emissions from electricity consumption in the operation phase (Environment Bureau, 2017). In order to achieve a green global economy, lifecycle assessment (LCA) is increasingly adopted to realize low carbon transition of the building industry (Nematchoua et al., 2019; Scrucca et al., 2020). LCA is applied to evaluate the energy use and environmental impacts of material production, construction, operation, and end-of-life phases. This worldwide trend has motivated the deployment and integration of innovative construction methods, design concepts and digital technologies such as modular/prefabricated construction and building information modelling (BIM) to reduce the lifecycle impact of buildings (Li et al., 2019; Mao et al., 2013).

Prefabrication involves manufacturing building components/assemblies in a factory before transporting and installing on site (Steinhardt and Manley, 2016). It has been proved to alleviate problems such as high construction cost, onsite waste generation, health and safety risks, and high energy use and carbon emission (Zhang et al., 2018). Hence, prefabrication has been globally adopted to reduce the environmental impacts of buildings. Based on the level of assembly in factory, prefabricated construction can be grouped into components (e.g. partition walls), non-volumetric assemblies (e.g. façades) and volumetric assemblies (e.g. kitchen pods). In Hong Kong, a densely populated city with high-rise buildings, the use of modular design and prefabricated construction is mainly promoted by the Housing Authority (HA). Early prefabricated construction dates back to mid-90s where prefabricated components/assemblies constituted 18% of the average volume of construction works by HA (HKHA, 2018). In 2002, the Building, Land and Planning Departments introduced a new guideline which popularized the use of non-structural precast façade in public residential buildings. In 2008, HA adopted modular flat designs which further increased the average prefabrication rate to 35% with volumetric precast bathrooms. By 2013, other precast components including precast acoustic balconies, precast roof/ground floor water tanks and precast roof parapets had been widely deployed (HKBD, 2019). A report indicated that prefabrication rate up to 65% is achievable (Li et al., 2016). More recently, the Development Bureau declared to complete the construction of prefabricated homes for students and employees by 2020. A pilot project, Innocell, which incorporates Modular Integrated Construction (MiC) – the most complete form of prefabrication – has been completed at the Hong Kong Science Park. Following this pilot project, selected government projects are expected to consider MiC from 2020 onwards. The Construction Industry Council has also investigated the feasibility of establishing prefabrication yards in Hong Kong to meet an estimated annual requirement (2017-2021) of 2,680,741 tonnes of prefabricated concrete components (HKCIC, 2018). As illustrated above, prefabrication has rapidly increased in high-rise public housing and shows prospects of even wider application in the future.

Besides prefabrication, transitioning towards a low carbon environment has also led to the emergence and application of digital technologies. One such technology is BIM, which has been widely explored in sustainability assessment (Ansah et al., 2019a; Wong and Kuan, 2014). BIM is a digital representation of a physical facility which serves as a repository for multidisciplinary data. It also has inherent capabilities to manipulate and generate data required for a wide range of building assessments (Andriamamonjy et al., 2019; Pezeshki et al., 2019; Santos et al., 2019a). In this context, the integration of BIM and LCA of buildings has been widely explored in recent studies (Soust-Verdaguer et al., 2017). BIM-based LCA can mitigate challenges of conventional LCA process, which is time-consuming, costly and involves manual data entry (Röck et al., 2018). Previous studies have leveraged this opportunity to promote different approaches for BIM-based LCA. One group of studies has simplified lifecycle inventory (LCI) by extracting bill of quantity (BOQ) from BIM tools (Basbagill et al., 2013; Georges et al., 2015; Hao et al., 2020; Kehily and Underwood, 2017; Peng, 2016; Shin and Cho, 2015) while another group of studies has defined workflows combining BIM, LCA and other auxiliary tools (Najjar et al., 2019; Nizam et al., 2018; Rezaei et al., 2019; Yang et al., 2018; Zhang et al., 2018). Both approaches mainly used BIM to extract

BOQs and missed the potential of BIM to store data and perform automatic LCA. A third group of researchers argue that the inclusion and manipulation of LCA data within BIM environment is a more effective approach to harness the power of BIM such as real time LCA during design changes (Cavalliere et al., 2018; Hollberg et al., 2020; Santos et al., 2019b; Shadram and Mukkavaara, 2018). In this regard, more recent approaches have used visual programming plug-ins with BIM tools such as Dynamo and Grasshopper or developed customized application programming interfaces (API) to perform BIM-based LCA.

Conceivably, this approach should be encouraged since it opens up several opportunities for fast real-time automated workflows. However, no study has applied the third approach to a systematic evaluation of prefabricated buildings in order to quantify lifecycle impacts at the various levels of prefabrication. Since existing studies did not consider various levels of prefabrication, they cannot provide systematic insights into the lifecycle performance of prefabricated buildings. With an increasing interest in systematic LCA of prefabricated buildings (Teng and Pan, 2020), it is inappropriate to ignore this research gap. Another limitation of current BIM-based LCA research is that the material production phase is usually the main focus whereas other lifecycle phases remain fairly unexplored. Meanwhile, studies indicate significant opportunities to reduce the embodied impacts of buildings through a combination transportation and end-of-life phase strategies (Chau et al., 2017). Therefore, the need to better integrate other lifecycle phases into BIM-based LCA can be clearly identified. To address these important gaps in BIM-based LCA, this study aims to (i) develop an automated BIM-based LCA approach for systematic evaluation of the whole lifecycle energy and environmental performances of prefabricated buildings; and (ii) demonstrate the framework by conducting a case study on a typical high-rise residential building in Hong Kong where up to 40% prefabricated components have been used. This study builds on the development of methods to integrate data within BIM model and the performance of real time LCA within the BIM environment. Primarily, it extends knowledge on automated BIM-based LCA by increasing the detail and accuracy of assessments while reducing time spent on the LCA of prefabricated buildings. Also, this study addresses the impact of construction, maintenance and replacement and end-of-life phases which have been overlooked in previous studies. The benefit of the proposed framework is validated against traditional LCA approaches. The developed framework and analysis results can also provide valuable references for industrial practitioners especially in high-density cities like Hong Kong where integrated BIM and prefabrication or MiC applications in the domain of low carbon designs are expected to gain momentum.

2. Methodology

A BIM-based framework is developed through LCA framework conceptualization, mathematical model formulation, and BIM-based simulation to support an automated LCA of prefabricated buildings, followed by demonstration through a case study. The methodology design focuses on both operationalizing the BIM-based method and detailing the results of a systematic whole lifecycle performance of a prefabricated building. The strength of the method is validated through a case study building which adopts up to 40% prefabricated components and three modular designs. The framework of the proposed BIM-based LCA is illustrated in Fig. 1, while details are described in subsections below.

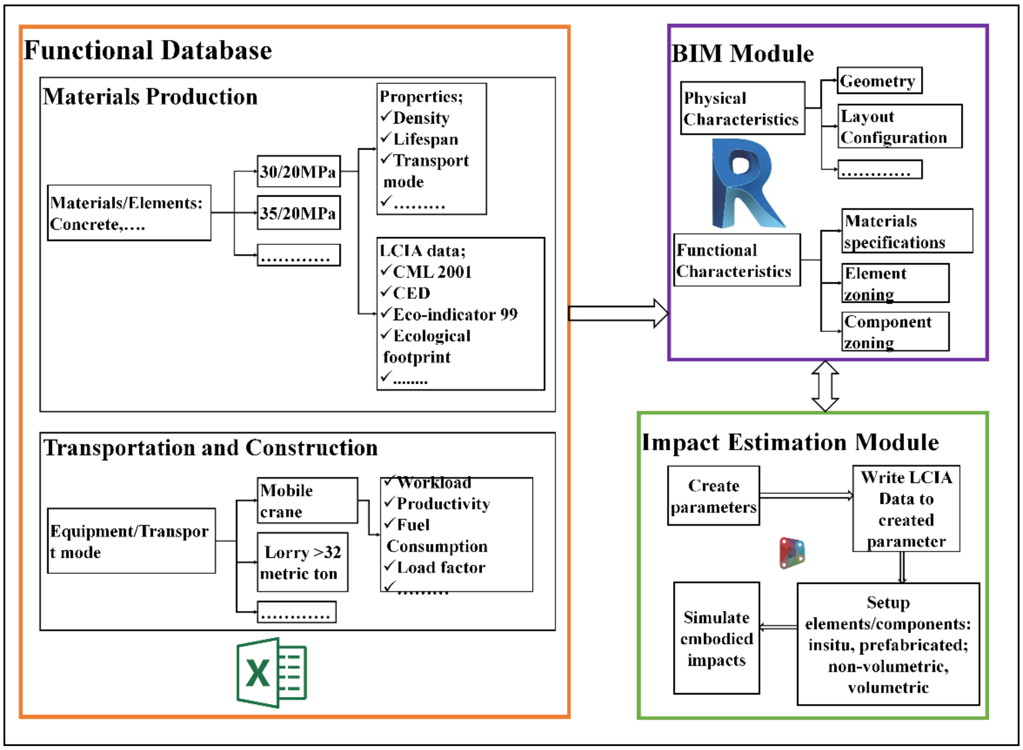


Fig. 1. Framework for the developed method

2.1. Framework for lifecycle assessment

The BIM-based LCA process is conducted in accordance with ISO 21931-1:2010 (ISO, 2010), ISO 14040 and ISO 14044 (ISO, 2006a, 2006b) following 4 steps: (i) definition of the goal and scope of LCA; (ii) lifecycle inventory analysis; (iii) lifecycle impact assessment (LCIA); and (iv) interpretation.

2.1.1. Goal and scope

The goal of this LCA is to perform a systematic energy and environmental assessment of a prefabricated building by integrating different assessment levels. A cradle-to-grave approach incorporating all life cycle phases of the building (material production, construction, use and end-of-life) is adopted. It also focuses on the structural and architectural elements of the superstructure without mechanical, electrical, and plumbing components since the latter is not a primary focus in reducing embodied impacts at the design stage. For the purpose of comparing LCA results, it is critical that the specific performance characteristics of buildings or building products are carefully defined. Hence the functional equivalent approach is used in this study to improve the accuracy and usefulness of the LCA results. The functional equivalent approach includes the type of building, relevant technical and functional requirements, Gross Floor Area (GFA) and reference service life. The technical and functional requirement as well as the reference service life are defined according to the Code of Practice for Precast Construction (Hong Kong Buildings Department, 2016). The functional equivalent used to evaluate the whole building and flat levels is expressed as per unit GFA and lifespan that meets the design requirement of public residential buildings in Hong Kong. For assemblies or components such as bathroom pods and beams, the functional equivalent is expressed as per standardized unit and lifespan that meets the design requirements of standardized precast elements used in Hong Kong. Table 1 illustrates the assessment levels, system boundaries and functional equivalent approach used in this study.

Table 1 Assessment level, system boundary and functional units used in this study

Assessment level	**System boundary**	**Functional equivalent**
Whole building level	Cradle to end-of-life phase	Gross Floor Area · year (m^2·y)
Flat levels	Cradle to end of construction phase	Gross Floor Area · year (m^2·y)
Assembly level (bathroom pods; façades; kitchen pods; refuse chutes)	Cradle to gate	Unit · year (u·y)
Component level (Beams; Columns; Doors; Floors; Stairs; Refuse chutes; Roof; Walls; Windows)	Cradle to end-of-life phases	Unit · year (u·y)

2.1.2. Lifecycle inventory

Lifecycle inventory involves compiling all input and output flows associated with the defined goal and scope of assessments. This step is critical to the subsequent stage if an appropriate LCA result will be achieved. As the main goal of the study is to develop a BIM-based LCA method for prefabricated buildings, all data required for the lifecycle inventory analysis are integrated into BIM environment. Also, the proposed levels of assessments are combined in this step for decomposition and categorization of building elements/components. Details on data integration and processing within BIM environment are provided in section 2.3.

2.1.3. Lifecycle impact assessment

Here, the result of the inventory analysis is used to quantify the energy and environmental impacts of the building. The energy use and environmental impacts at different lifecycle phases are estimated by multiplying the quantities of work by an appropriate impact factor. The calculation of energy use and environmental impacts are described in section 2.2. Two LCIA methods from the Ecoinvent database v.3.5 – CML 2001 and Cumulative Energy Demand (CED) – are selected for the case study. The CML 2001 is widely used and provides a good basis for comparison of results with other studies. Also, the impact categories of CML 2001 is not aggregated by weight to provide transparency (Kouloumpis et al., 2020). However, impact categories of CED are aggregated as they are measured in the same unit. Since most previous studies did not address the whole lifecycle energy use of prefabricated buildings, this study extends knowledge in the domain by including CED. Impact categories of the CML 2001 method include Abiotic Depletion (ADP-f) (kg Sb-eq), Acidification Potential (AP) (kg SO2-eq), Eutrophication Potential (EP) (kg PO4-eq), Fresh Water Aquatic ecotoxicity (FAETP) (kg 14-DB-eq), Global Warming Potential (GWP) (kg CO2-eq), Human Toxicity Potential (HTP) (kg 14-DB-eq), Marine Aquatic Ecotoxicity (MAEP) (kg 14-DB-eq), Ozone Layer Depletion (ODP) (kg CFC-11-eq), Photochemical Oxidation (POCP) (kg C2H2) and Terrestrial Ecotoxicity (TETP) (kg 14-DB-eq). The impact categories of the CED method includes renewable and non-renewable energy categories. The renewable energy categories include Biomass (MJ-Eq), Geothermal (MJ-Eq), Solar (MJ-Eq), Water (hydropower) (MJ-Eq) and Wind (MJ-Eq) whereas the non-renewable energy categories include Fossil (MJ-Eq), Nuclear (MJ-Eq) and Primary Forest (MJ-Eq).

2.1.4. Interpretation

Lifecycle interpretation is a systematic step to evaluate the results from the lifecycle inventory analysis and lifecycle impact assessment. In this stage, the result is structured in a manner that is consistent with the goals and scope of the study. The results should be presented in a manner that is easily interpretable so that scenarios and variability in input data can be integrated to improve the performance of the building. Finally, conclusions, limitations, recommendations, and guidelines with respect to the goal are provided for decision-making.

2.2. Calculation of lifecycle impacts

A generic model is applied to illustrate the calculation of energy and environmental impacts. This model is applied for all indicators investigated in this study based on the primal rule as shown in Eq. (1) (Zhang and Zheng, 2020):

$$\mathrm{EP} = \mathrm{Q} \times \mathrm{IC} \tag{1}$$

where EP, Q, and IC represents the energy or environmental impacts, activity quantity and impact coefficient, respectively. Eq. (1) is then expounded to suit different lifecycle phases in the following sections.

$$\mathrm{EP} = \mathrm{EI} + \mathrm{OI} \quad (2)$$

where EP is the total lifecycle impacts, EI is the embodied impacts and OI is the operational impacts.

2.2.1. Embodied impacts

The embodied impacts are defined to include energy uses and carbon emissions from the material production, transportation, construction, building maintenance and end-of-life cycle phases. Thus, the total embodied impacts (EI) are given by Eq. (3):

$$\mathrm{EI} = \mathrm{EI_m} + \mathrm{EI_t} + \mathrm{EI_c} + \mathrm{EI_{bm}} + \mathrm{EI_e} \quad (3)$$

where, EI_m, EI_t, EI_c, EI_{bm} and EI_e represent the impacts from material production, transportation, construction, building maintenance and end-of-lifecycle phases, respectively.

2.2.1.1. Material production phase

The impacts from the material production phase include: (i) in-situ and (ii) prefabricated components. Insitu components relate to the raw material production only, whereas precast components include the impacts from transporting and manufacturing of precast components in the prefabrication factory.

EI_m from the material production phase is given by Eq. (4):

$$\mathrm{EI_m} = \mathrm{EI_{mc}} + \mathrm{EI_{mp}} \quad (4)$$

where EI_{mc} is the impact from the production of insitu elements; and EI_{mp} is the impact from precast elements.

EI_{mc} from the production of insitu materials is given by Eq. (5):

$$\mathrm{EI_{mc}} = \sum_{i=1}^{n} Q_p \left(1 + w_f\right) \times IC_p \quad (5)$$

where n is the number of different building materials i; Q_p is the quantity of materials; W_f is the wastage factor and IC_p is the impact coefficient.

EI_{mp} from the production of prefabricated components is given by Eq. (6) :

$$\mathrm{EI_{mp}} = \mathrm{EI_{mp1}} + \mathrm{EI_{mp2}} + \mathrm{EI_{mp3}} \quad (6)$$

where $\mathrm{EI_{mp1}}$, $\mathrm{EI_{mp2}}$, and $\mathrm{EI_{mp3}}$, represent the impacts generated from material production, transportation to factory and manufacturing of prefabricated components, respectively.

$\mathrm{EI_{mp1}}$ from the material production of prefabricated components is expressed by Eq. (7):

$$\mathrm{EI_{mp1}} = \sum_{c=1}^{m} \sum_{i=1}^{n} Q_t \times IC_p \quad (7)$$

where Q_t is the quantity of each material *i* used in precast component c; *m* and *n* are the total number of precast components and materials, respectively; IC_p is the impact coefficient for material *i*.

$\mathrm{EI_{mp2}}$ from the transportation of materials to the prefabrication factory is expressed by Eq. (8):

$$\mathrm{EI_{mp2}} = \sum_{i=1}^{n} Q_t \times IC_t \quad (8)$$

where Q_t is the quantity of material *i* (ton.kilometer) to be transported to a prefabrication factory; IC_t is the impact coefficient for the transport mode.

$\mathrm{EI_{mp3}}$ from manufacturing of prefabricated components is expressed by Eq. (9):

$$\mathrm{EI_{mp3}} = \sum_{e=1}^{f} \sum_{c=1}^{m} Q_{p.c} \times E_{\ p.e} \times IC_{\ p.e} \quad (9)$$

where $Q_{p.c}$ is the production volume of prefabricated component *c*, which requires energy type e; $E_{p.e}$ is the mass of energy for the production of the unit volume of *c*; $IC_{p.e}$ is the impact coefficient of the energy type *c*; *f* and *m* represent the total number of energy types and precast components respectively.

2.2.1.2. Transportation phase

The impacts generated from transportation consist of the total energy use and emission incurred from delivering insitu materials and prefabricated components via different modes of transportation. $\mathrm{EI_t}$ from transportation is given by Eq. (10):

$$\mathrm{EI_t} = \sum_{p=1}^{x} \sum_{o=1}^{y} Q_t \times IC_{t.m} \times l_f \quad (10)$$

where Q_t is the quantity of material/element/assembly *o* (ton.kilometer) to be transported by method *p*; IC_t is the impact coefficient for transportation mode *p; l_f* is the load factor; *x* and *y* are the total transportation modes and materials/components, respectively.

2.2.1.3. Building construction phase

The impacts from the building construction phase consist of energy use and emissions from onsite construction equipment. Major on-site construction equipment includes the tower crane, truck-mounted crane, truck-mounted concrete pump, hoist, and forklift. EI_c from construction is given by Eq. (11):

$$\mathrm{EI_c} = \sum_{q=1}^{z} \sum_{w=1}^{v} Q_c \times \mathrm{E}_{p.e} \times IC_{c.e} \quad (11)$$

where Q_c is the amount of work *w* which uses equipment type *q*; $E_{p.e}$ is the mass of energy used by equipment type *q* for work *Qc*; $IC_{p.e}$ is the impact coefficient of energy type $E_{p.e}$; and *z* is the total number of equipment for work type w. The building construction data are sourced from a research paper and a consultancy study on building LCA by the Electrical and Mechanical Service Department in Hong Kong (EMSD, 2006; Nizam et al., 2018).

2.2.1.4. Building maintenance phase

The energy uses and emissions from maintenance are estimated according to the reference service life of building materials and components. It is assumed that periodic maintenance activities including painting, rendering, replacement of windows are performed as the service building life exceeds those of some materials. In such scenarios, the differences are addressed as recurrent materials using replacement factors sourced from relevant literatures (Chau et al., 2007, 2006; Dixit, 2019).

EI_{bm} from the building maintenance phase is given by Eq. (12):

$$\mathrm{EI_{bm}} = \sum_{i=1}^{n} [(Q_p \times R_f) \times (1 + W_f)] \times IC_p \quad (12)$$

where *n* is the number of different building materials or prefabricated component *i used for repairs or replacement*; Q_p is the quantity of materials or prefabricated components; R_f is the replacement factor; W_f is the wastage factor and IC_p is the impact coefficient.

2.2.1.5. End-of-life phase

The end-of-life phase includes energy and emissions related to building demolition and transportation for landfills or recycling. It is assumed that an excavator, a wheel loader and trucks are used for demolishing and transportation. Each material is considered for recycling or landfills and the net impact is estimated based on whether it joins other processes or exits the material flow completely. Based on the practice in Hong Kong (Hossain and Ng, 2019), it is assumed that steel is recycled while concrete and other non-inert materials such as wood, glass and plastics are sent to public landfills. It is assumed that only half of steel used in the building is recovered. Thus, after demolition, half of steel used in the building is recovered while all other materials are landfilled. The impact of the end-of-life phase (EI_e) is given by Eq. (13):

$$\mathrm{EI_e} = \sum_{i=1}^{g} Q_r \times (E_{ee} - E_{re} - E_t) \quad (13)$$

where Q_r represents the percentage of total material *i* to be recycled or landfilled; E_{ee} represents the impact coefficient of the material i, E_{re} represents the impact incurred in demolishing process; E_t is the impact incurred from transporting materials from the demolishing site to the landfill or recycling plant; and g is the total number of materials to be demolished.

2.2.2. Building operation phase

The operational impact consists of energy and emissions from building operation (i.e. cooling, cooking, daily hot water, lighting, and other appliances) for a 50 year reference study period which is equal to the service life of the case building. Building system and occupancy schedules are used to calculate occupational heat gains and operational energy demands. Emission factors are then applied to calculate the total emission during the operation phase. The impacts from building operation (OI) are given by Eq. (14):

$$\mathrm{OI} = \sum_{e=1}^{f} \sum_{l=1}^{u} Q_{bo} \times IC_{c.e} \quad (14)$$

where Q_{bo} is the quantity of activity *l* which requires the energy type *e;* and *u* is the total number of activities during the operation phase of the building. The building energy use is simulated in Green Building Studio. Two energy sources are used during the operation phase (i.e. electricity and liquified petroleum gas). Table 2 and Fig. 2 illustrates the energy simulation parameters and the building operation schedule, respectively.

Table 2 Illustrates the energy simulation parameters for the operational energy uses (Chen et al., 2015)

Parameter	**Value**	**Unit**
External wall thermal resistance	0.09	m2 K/W
External wall specific heat	840	J/kg K
External wall solar absorptance	0.60	-
Wall U-value	2.30	W/m^2 ◦C
Roof U-value	0.35	W/m^2 ◦C
Window U-value	5.99	W/m^2 ◦C
Window solar heat gain coefficient	0.57	-
Lighting Load	15	W/m2
Occupant Load	100	W/person
Misc. Equipment Load	142	W

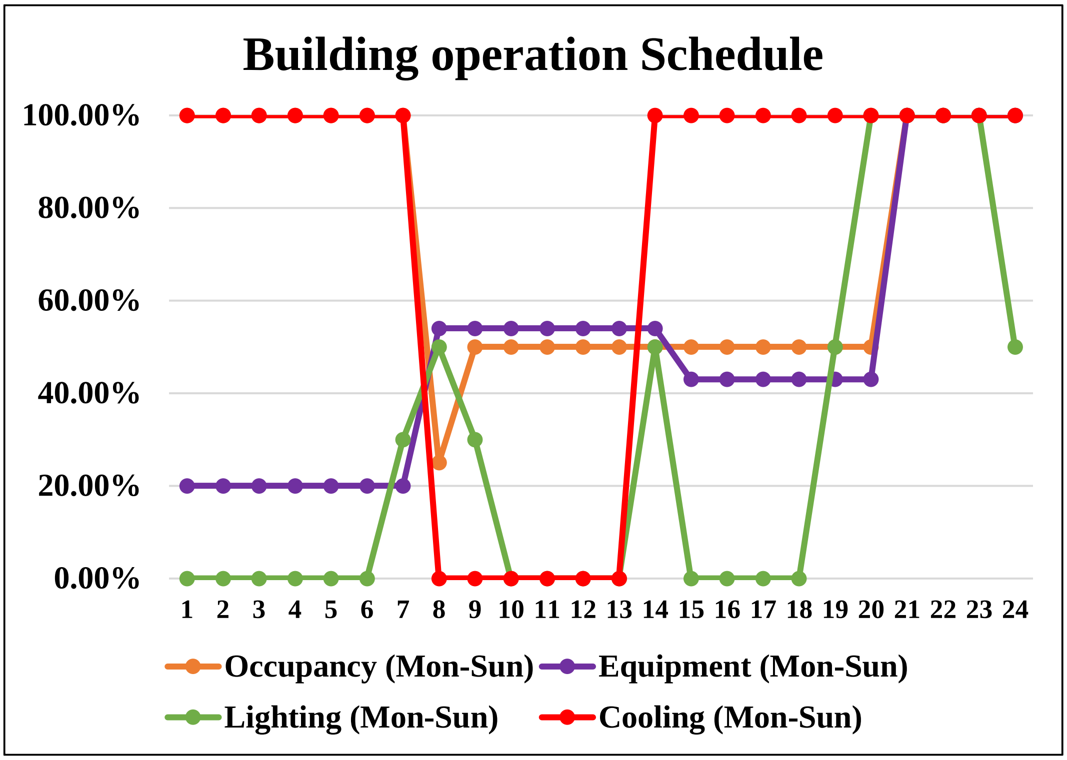


Fig. 2. Occupancy, lighting, cooling and equipment schedule for the building

2.3. Integrating BIM and LCA for prefabricated buildings

Since the main objective of this study is to develop a comprehensive BIM-based method to support automated LCA of prefabricated buildings at different levels of assessments, this section details data integration process within BIM environment. Autodesk Revit is selected as the BIM tool, as it can handle a wide spectrum of sustainable information including LCA data. Moreover, it embeds Dynamo as a visual programming tool that can be used for LCA. In addition, Microsoft Excel is integrated to create a database and serve as an output interface for LCA results.

2.3.1. Data repository

The fundamental component of the method is a functional database since LCA implementation is impossible without pertinent data. The functional database includes all possible material options for prefabricated buildings in Hong Kong. The first step is to develop a comprehensive material/component list, followed by the establishment of properties relevant to the assessment of all lifecycle phases. This include material's density, lifespan, construction/demolition equipment, transportation modalities and lifecycle impact coefficients/factors for various materials or activities. These data are catalogued in relationships (i.e. each material/component with a set of parameters in Excel) so that their retrieval is simplified for subsequent stages. Fig. 3 shows a section of the developed database. LCIA data are sourced from Ecoinvent (Weidema et al., 2013) while supplementary information such as material wastage, and lifespan are sourced from literature. The emission factors were adapted to reflect the particularities of Hong Kong by adjusting the transportation distances and transportation mode with available local data from experts. Furthermore, the fuel mix for electricity production was also adjusted to reflect the electricity production in Hong Kong and Mainland China. The mix and strength of materials such as concrete are also adjusted per data retrieved from experts. The established impact assessment data are categorized into lifecycle phases and include all LCIA methods provided by Ecoinvent.

The material production phase includes the impact of producing materials/components from the extraction of raw materials to the end of manufacturing. For some materials such as concrete and steel, several subcategories are included to account for different strengths or grades. The functional units vary in Ecoinvent so that the database is designed to support conversions between units. Environmental performance data on the transportation phase include three modes of transport (i.e. sea vessels, trucks, and rails) with different loading capacities and distances sourced from (Chau et al., 2012). Especially, different loading factors are considered for prefabricated and insitu components. The productivity, workload, fuel consumption of equipment for different work items are also included in this functional database to evaluate the construction phase as sourced from (Nizam et al., 2018). For the end-of-life phase, the developed database includes the productivity, fuel efficiency, energy conversion factors and environmental impacts of equipment used for the demolishing and transportation to recycling or landfill sites. As mentioned earlier it is assumed that an excavator, wheel loader and trucks are used at the end-of-life phase. Details on demolishing processes and requirements are sourced from (HKBD, 2004).

A naming convention is adopted to assign a unique ID to each item in the database to facilitate automated matching of data. The database is developed manually in Microsoft Excel as part of a future study to optimize the embodied impacts of prefabricated buildings. New materials can be easily added using the predefined naming convention. Automated queries to and from the database are described in section 2.3.3.

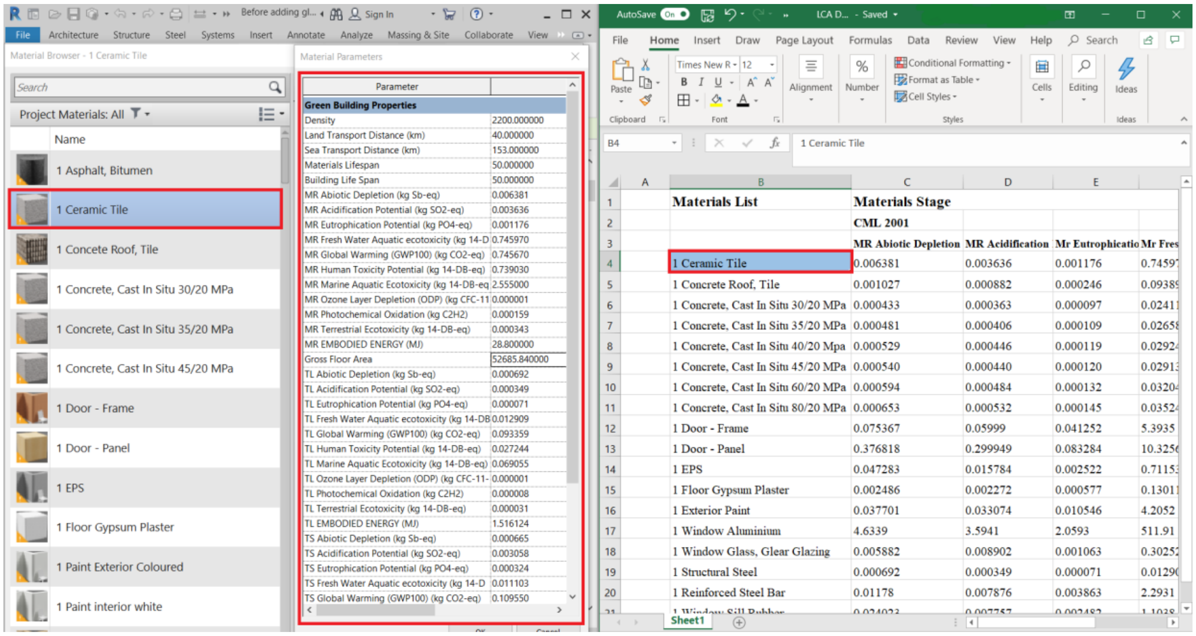


Fig. 3. Developed database and naming convention in the BIM model

2.3.2. BIM module

Autodesk Revit BIM tool is selected due to its inherent capabilities to support the development of the impact estimation module, eliminating challenges of interoperability. It enables building detailed 3D models and defining specific layers of construction materials. Also, its detailed scheduling function can generate geometric data which are particularly useful for embodied impact assessment (Ansah et al., 2019b). The first step is to develop BIM model which includes physical and functional characteristics (Gan et al., 2018). Physical characteristics comprise geometries and layout configurations while functional characteristics include material specifications, element and component zoning. It is important to establish a consistent modelling workflow to produce an accurate LCA result. The BIM model must be developed using the same naming conventions in the developed material database as illustrated in Fig. 3. It is critical to populating the BIM model with LCA data. Also, all elements must be tagged prefabricated or insitu through a parameter at the instance level. Since the native BIM element classification is not favorable for a prefabricated inventory analysis, a zoning technique is introduced to group composite elements. This technique can be applied to group for instance, concrete and reinforcement bars of a reinforced concrete column. Similarly, the zoning technique can group prefabricated components at volumetric (kitchen/washroom pods) or non-volumetric (façade) levels so that their impacts can be assessed appropriately. This technique is also applied at the flat level since public residential buildings in Hong Kong use standardized flat designs.

2.3.3. Impact estimation module

The impact estimation module is a computational script using nodes and codes to write the required LCA data to the BIM model, process the data and provide the lifecycle impacts of prefabricated buildings. It is realized in Dynamo, a built-in computational tool of Autodesk Revit, whose unlimited nodes provide endless opportunities to customize tasks and generate desired results. Moreover, Dynamo's support for Python and C# facilitates the development of custom scripts or packages, some of which are used to connect an external database to Revit. The script is split into parts and executed in chains to increase the computational efficiency and track errors quickly. The steps involved in the impact estimation module are discussed as follows.

The first step is to create parameters for all materials/components in order to write LCA data from the functional database to the building model. As the database comprises numerous impact assessment methods, this step enables users to select parameters suited to their desired LCIA method. Thereafter, a second interface writes the impact assessment data to the created parameters. Fig. 3 shows a sample of data written to a ceramic material in the Revit library. The naming conventions used in the database is kept for an automatic execution. An intelligent match of the impact assessment data with the method selected in the previous step is achieved with Structured Query Language (SQL), which queries data such as the impact coefficient from the functional database and writes automatically to created parameters.

The next step involves setting up materials/components and is critical to producing an appropriate prefabricated/insitu inventory. Here, the parameter assigned at the instance level during modelling is used to determine whether an element/component is insitu or prefabricated. A set of constrains is then applied to each element/component, such as transportation modalities including partial loads, types of vehicles or vessels and types of construction equipment. Wastage factors depending on the type of materials and mode of construction are also assigned in this step.

After setting up elements/components, a customized quantity takeoff and impact factors for each lifecycle phase is extracted into Dynamo. For most parts, the volume of each material is derived from multiplying its area by its thickness while the mass is obtained as a product of its volume and density. For some materials/elements such as rebars and windows, the estimation method is adapted as geometric information extracted from these elements cannot produce an accurate result. The impact assessment is then performed by intelligently matching each material with the appropriate LCA data. Finally, a report containing the embodied impacts of the model is generated in accordance with the various levels of assessments.

The automation process is a major contribution of the developed method which expedites the assessment process in Dynamo. Originally, a large number of nodes in the designed scripts resulted in longer computational time especially when combined with large number of elements in a high-rise building. To reduce the number of nodes, this study first utilized list management functions and extracted similar parameters with a single node. However, it yielded limited improvement. An effective solution was then proposed to convert nodes into codes and simplify them in Python wherever possible. This approach reduced the number of nodes and computational time significantly. To track errors, the entire script is first split into stages discussed above and run consecutively in Dynamo Player. At the final stage of the impact assessment, a unique script is run for each level of assessment, reducing the computational time as required. A sample script to evaluate the impacts of roof is presented in Fig. 4, which illustrates how multiple nodes are combined into a single code to improve computational efficiency.

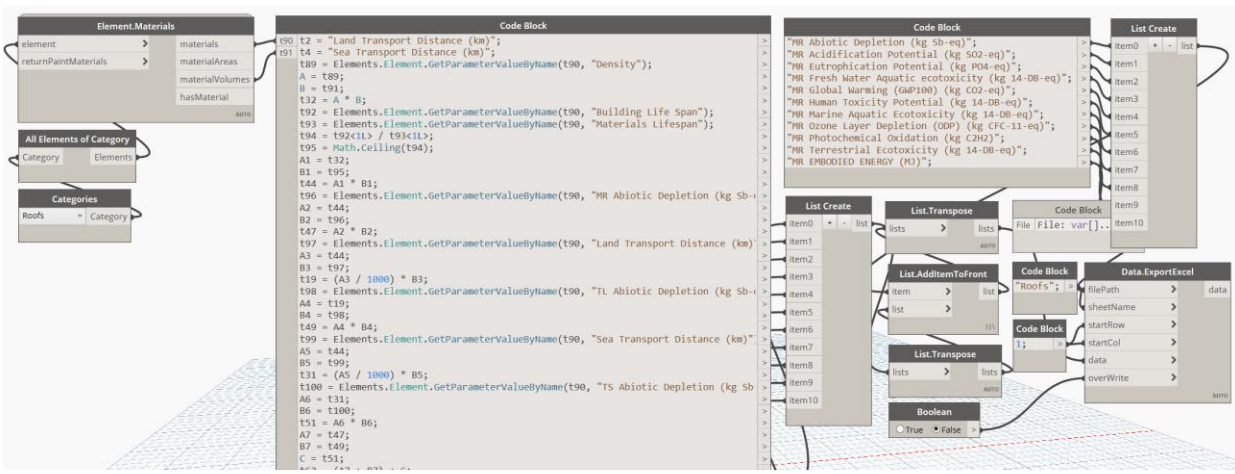


Fig. 4. Sample script to estimate the lifecycle impacts of roof

2.4. Case study building

The developed method is applied to a prefabricated residential building in Hong Kong. The selected case study can represent the general characteristics of most newly constructed public rental housing. The case building has 40 floors with a single floor height of 2.75 m. It features a reinforced concrete structure with 40% precast elements including precast façades, slabs, connecting slabs, kitchen/bathroom pods, stairs and refuse chutes. The building is modularly designed and contains standardized assemblies and 24 standardized flats (i.e. 7 two-person-three-person flat (2P3P), 12 one-bedroom flat (1B) and 5 two-bedroom flat (2B)) on each typical floor. Fig. 5 illustrates the standardized flats and some precast components used in the building. The floor plan and BIM model are shown in Fig. 6 while the main characteristics are provided in Table 3. The gross floor area (GFA) and total building height are 52685.50 m^2 and 130 m, respectively. A 50-year lifespan is uniformly specified for all assessments while system boundaries and functional units vary with assessment/prefabrication levels as per Table 1. The BIM model of the case building is developed in Autodesk Revit. After creating necessary parameters and applying zoning techniques, the rest of the assessment process is automated in Dynamo player. Subsequent runs after initializing the model take three minutes on average, indicating a high computational efficiency.

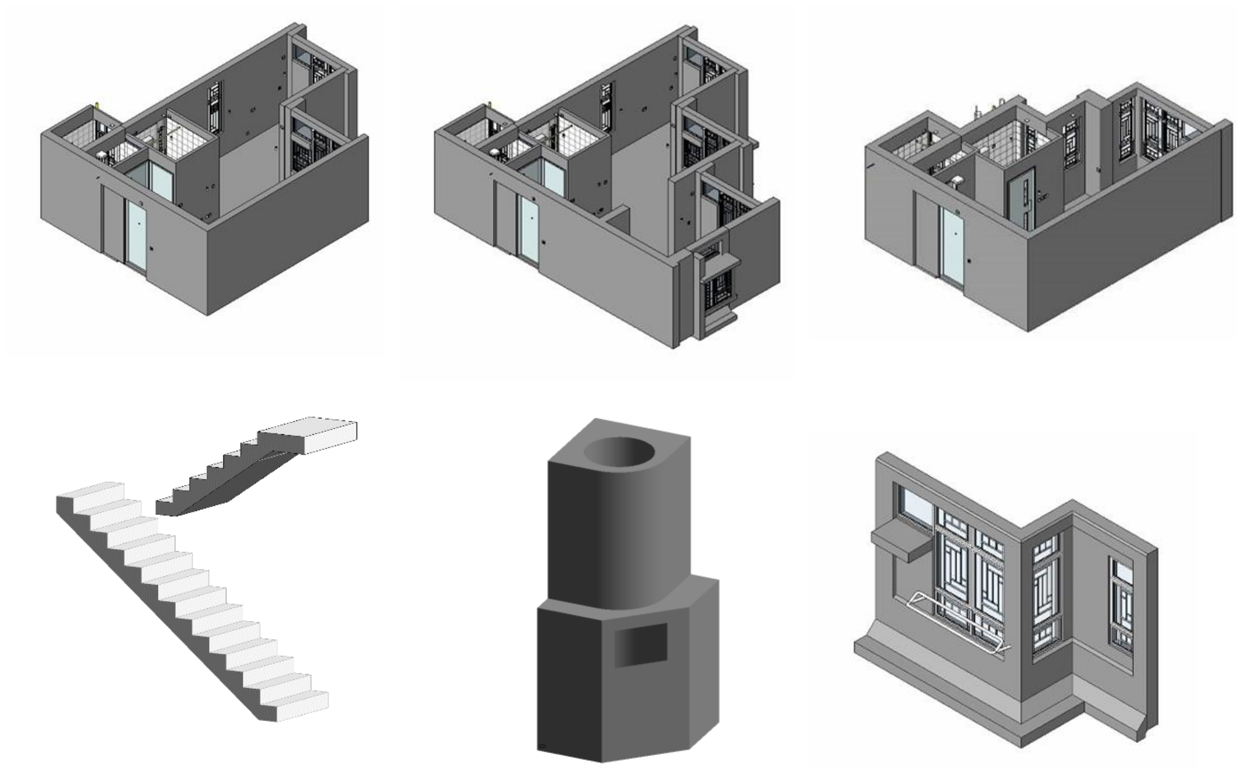
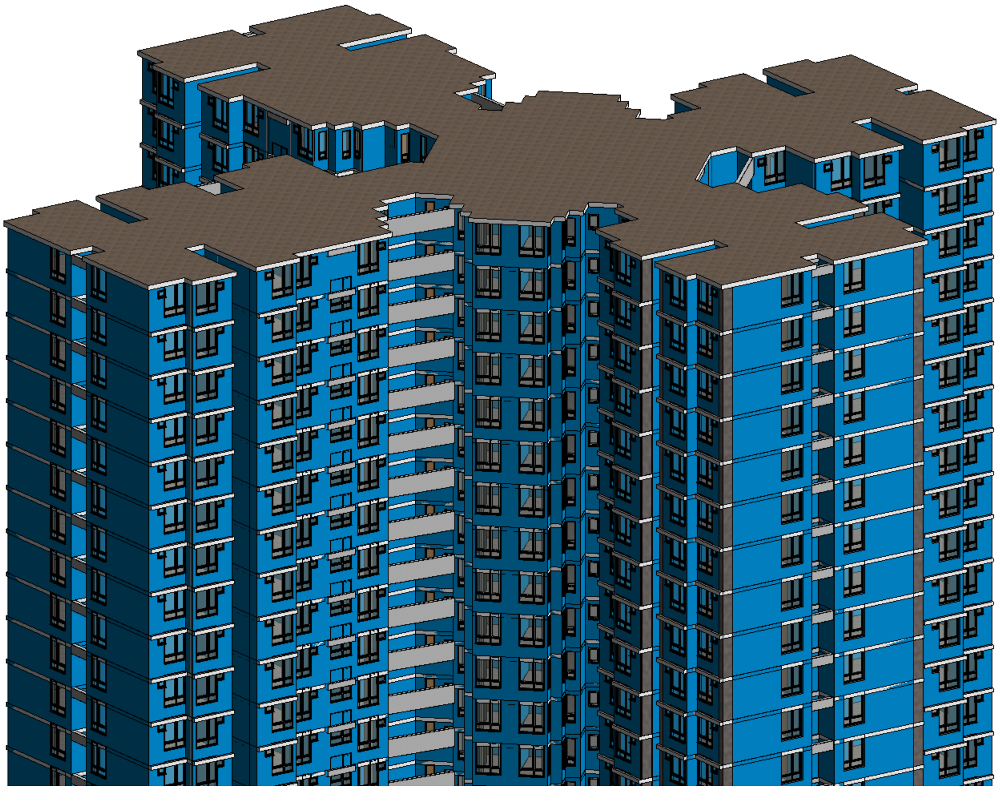


Fig. 5. Modular flats and samples of prefabricated components used in Hong Kong Public residential buildings

Table 3 Characteristics of case building

Building parameter	**Specification**
Floor height	2750 mm
GFA	52685.50 m^2
Number of floors	40
Number of units	960
Structure	Reinforced concrete, precast units
Level of prefabrication	40%
Walls	200 mm or 250 mm Structural cast-insitu concrete walls with steel reinforcement, cement sand plaster, paint finish Precast façades
Upper floor slabs	70 mm precast slabs, 90 mm cast-in-situ concrete
Openings (Doors and Windows)	Hollow core hardwood doors with hardwood frame and metal fixtures Aluminum framed windows with 6 mm clear float glazing

Lifespan	50 years



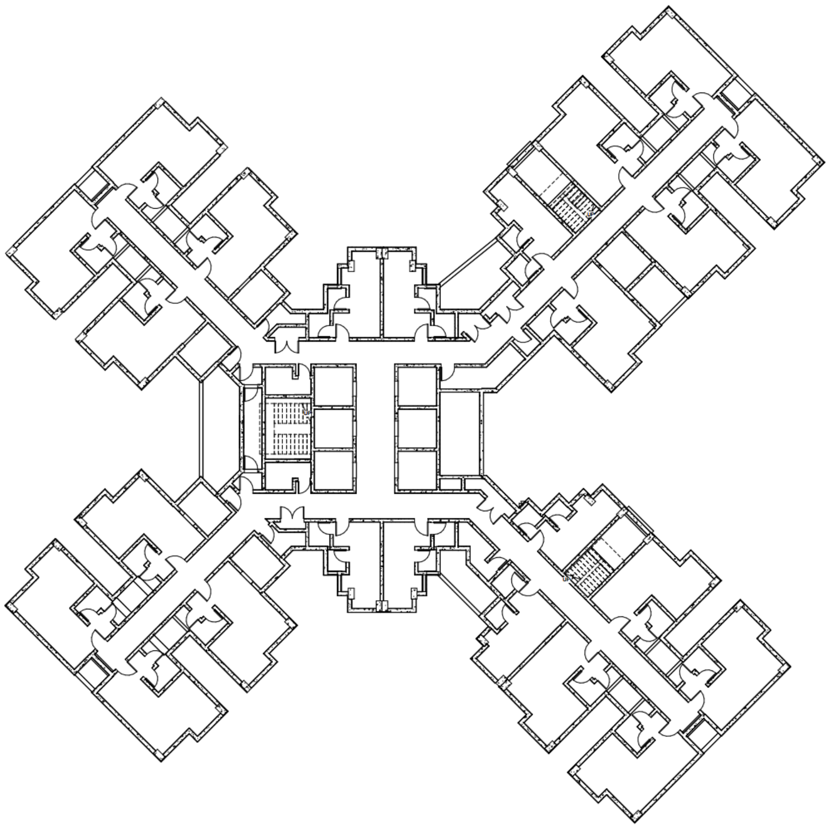


Fig. 6. Floor plan of case building

3. Results

Using the designed methodology, LCA is automated to provide deep insights of the energy and environmental performances of the case building. This section highlights results of an inventory of materials/components and the lifecycle impacts through the studied indicators. Important findings are presented and analyzed at four levels of assessments with unique functional units and system boundaries. For the purpose of simplicity and clarity, the results are presented according to embodied impacts and operational impacts where the embodied impacts include materials production, construction, transportation, building maintenance and the end-of-life phase. On the other hand, the operation impacts entail impacts from energy uses during occupation of the building. The embodied impacts are further stratified according to the different levels of assessments and their defined system boundary presented in Table 1.

3.1. Profile of inventory

The designed tool produced a profile of materials/components used in the case building. Table 4 summarizes the inventory of precast elements and insitu materials by weights. Studies have shown that efficient waste minimization still remains a challenging issue in Hong Kong (Mak et al., 2019). Even after implementation of waste reduction strategies, a significant amount of waste is still generated during the construction process (Wu et al., 2019). Therefore, the inventory of materials and precast elements is adjusted to account for these waste generation using waste factors of materials and components sourced from literature (Jaillon et al., 2009). Cementitious materials and steel dominate the material inventory which is a common trend for buildings in China (Huang et al., 2019). The total weight of building materials is 78,102,203.00 kg or 1,482.41 kg/m^2, where precast components and materials used on site contribute 40.27% (558.05 kg/m^2) and 59.73% (885.52 kg/m^2), respectively. Splitting between materials used on site, in-situ concrete contributes 48.59% (702 kg/m^2) followed by cement plaster 4.38% (64.92 kg/m^2), steel reinforcement in in-situ concrete 2.95% (43.70 kg/m^2), timber 2.38% (35.32 kg/m^2), ceramic tiles 0.98% (14.47 kg/m^2), glass 0.23% (3.36 kg/m^2), stainless-steel and others 0.19% (2.86 kg/m^2), paint 0.04% (0.53 kg/m^2), and asphalt 0.01% (0.05 kg/m^2).

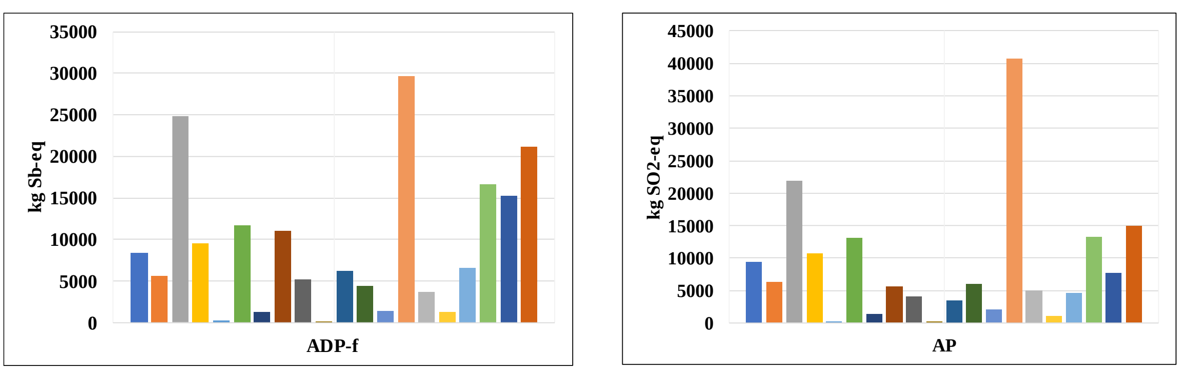
Table 4 Inventory of materials/elements

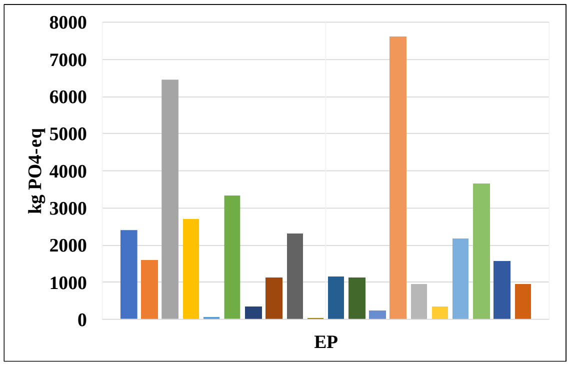
Material	**Element/Component/Assembly**	**Quantity (tonnes)**	**Waste factor**
Aluminum	Windows frames	22.125	1.05
Asphalt	Damp-proof; roof covering	2.7	1.05
Cement plaster	Beams; columns; facades; bathroom/kitchen pods; structural walls; floors; ceiling	3420.177	1.10
Ceramic tiles	Walls; slabs	762.375	1.10
Glass	Windows	177	1.025
In-situ concrete	Beams; columns; structural walls; slabs; roof	35,949.98	1.05
Paint	Beams; columns; facades; bathroom/kitchen pods; structural walls; floors; ceiling	28.08	1.05
Steel reinforcement in in-situ elements	Beams; Columns; Structural walls, roofs	2302.256	1.03
Steel reinforcement in precast elements	Façades; staircases; refuse chute; kitchen/bathroom pods; slabs; connecting slabs; beams	2024.75	1.01
Stainless-steel	Metal doors; windows; metal grills etc.	150.76	1.03
Timber	Doors; formwork	1860.75	1.07
Precast concrete	Façades; staircases; refuse chute; kitchen/bathroom pods; slabs; connecting slabs; beams	28,701.25	1.01

3.2. Embodied impacts at the whole building level

The overall embodied impacts in GWP and CED are 12.85 kg CO_2 eq/m^2·year and 0.16 GJ/m^2·year. This estimate includes all impacts from material extraction, transportation to site/factory-to-site, onsite construction processes and end-of-lifecycle. For clarity and comparison with previous studies, GWP and CED are highlighted in the analysis and discussion. Considering different lifecycle phases, material and component production contributes the highest impact in both GWP and CED (76.98% and 80.22%), followed by transportation (10.01% and 9.07%), onsite construction (7.96% and 7.19%) and finally the end-of-life phase (5.05% and 4.58%). Transportation of precast components contributes up to 50% of the transportation impact due to partial loads and long hauling distances (Dong and Ng, 2015). This validates the need to establish prefabricated factories in closer proximity to construction sites.

Fig. 7 depicts the contribution of each material and precast component to the embodied impacts of the case building. For prefabricated components, façades generate the highest impact on both GWP and CED (7.77% and 8.09%), followed by kitchen pods (5.62% and 5.86%), bathroom pods (4.93% and 5.14%), slabs (4.06% and 4.23%), connecting slab (2.16% and 2.25%), stairs (0.79% and 0.82%) and refuse chute (0.14% and 0.14%). For materials used on site, cast-in-situ concrete contributes the highest GWP and CED (27.98% and 29.16%), followed by steel reinforcement (8.98% and 9.39%), timber (6.46% and 6.73%), plaster (2.59% and 2.69%), aluminum (2.08% and 2.17%), ceramic tiles (2.05% and 2.14%), glass (0.68% and 0.71%), paint (0.64% and 0.67%) and asphalt (0.04% and 0.04%). Varying trends are observed when comparing the impacts of materials/components across different indicators. Taking insitu concrete as an example, although it has the highest impact on ADP-f, AP, EP, GWP and CED, its impact on HTP, FAETP and TETP is relatively low because of the higher impact factors of other materials and components. Therefore, it is necessary to report different impact categories for a comprehensive LCA.

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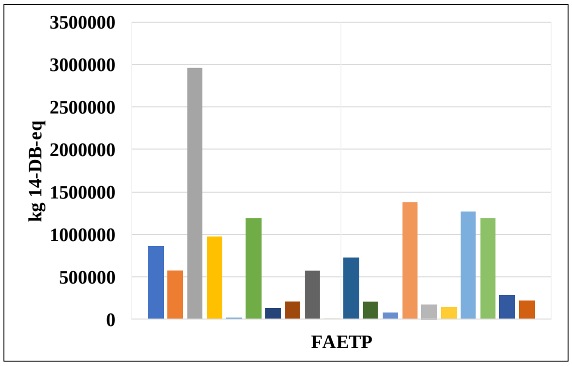
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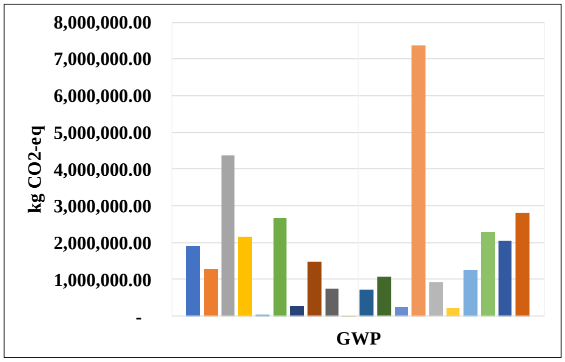
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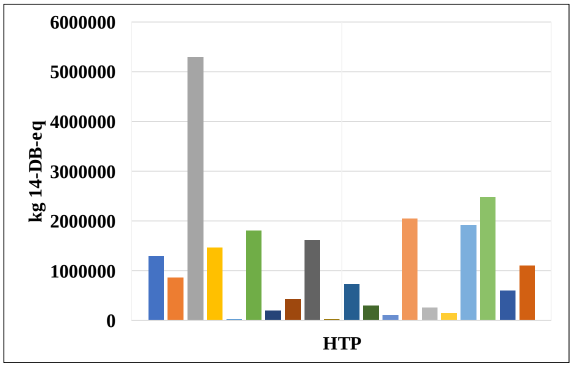
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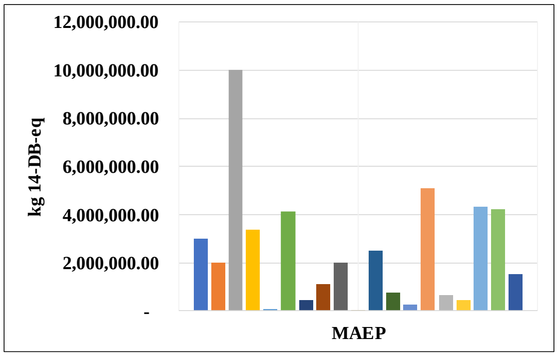
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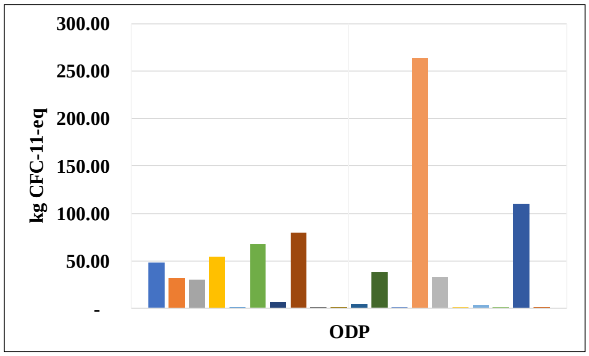
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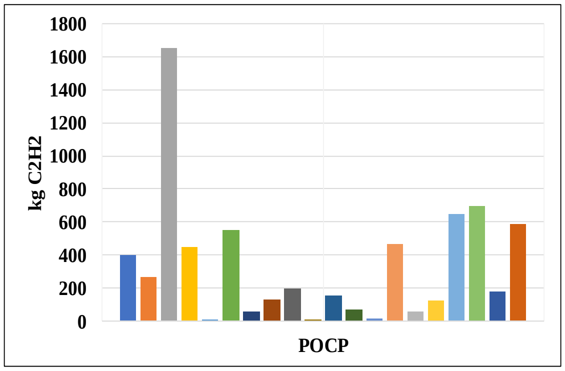
ODP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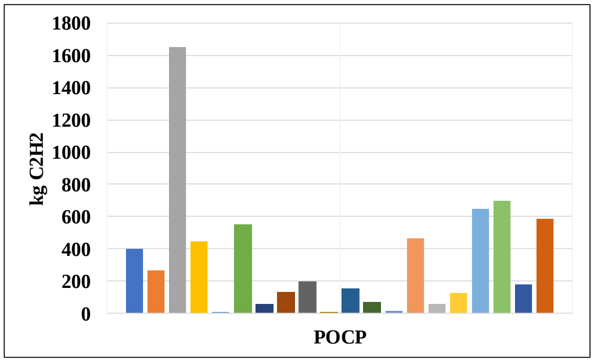
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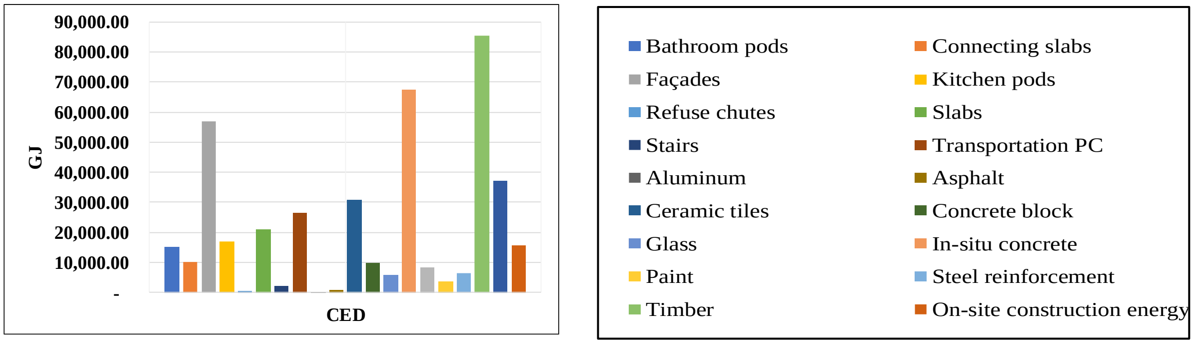
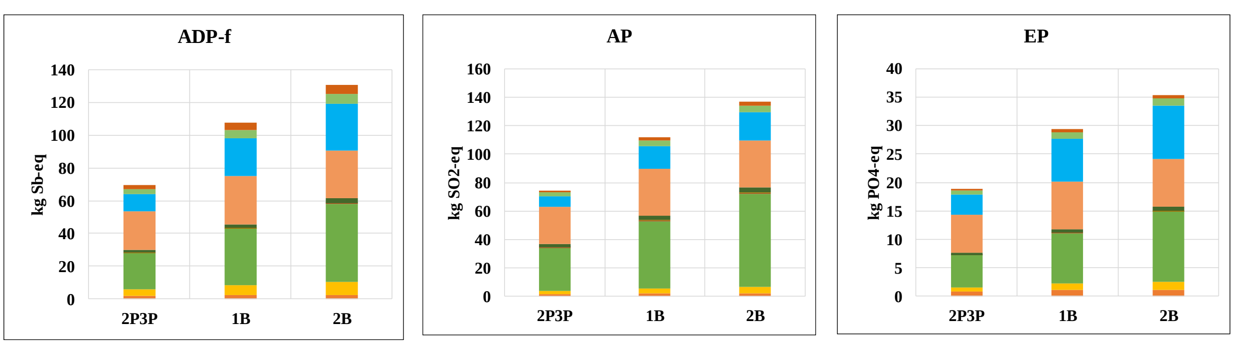


Fig. 7. Life cycle impacts at the whole building level

3.3. Embodied impacts at flat level

Public rental buildings in Hong Kong adopt modularly designed standardized flats so that it is useful to evaluate and compare the performance of different flat types as a guide for the design of future buildings. By adopting the types with lower energy and environmental impacts per unit area, the overall impacts of the building can be further reduced. Fig. 8 compares embodied impacts of three standard flats (2P3P, 1B and 2B) used in the case building. The results at flat level consist of impacts from material consumption, transportation, and energy use on site. Consistent trends are observed in the contribution of each material across the studied impact categories except ODP. The mean CED and GWP per flat are 134,984.17 MJ and 14,935.95 kg CO_2, 193,204.56 MJ and 21,190.32 kg CO_2 as well as 252194.74 MJ and 27,818.07 kg CO_2 for Flat 2P3P, Flat 1B and Flat 2B respectively. If Flat 2P3P is used as baseline, an increase of 53% and 87% is observed for Flat 1B and 2B respectively. However, when compared per floor area, Flat 1B has 3% and 10% less impact than Flat 2P3P and 2B, and is therefore validated as the most favorable flat design (Teng and Pan, 2019). The contribution of each component or material in CED, GWP and other studied indicators is also presented in Fig. 8.



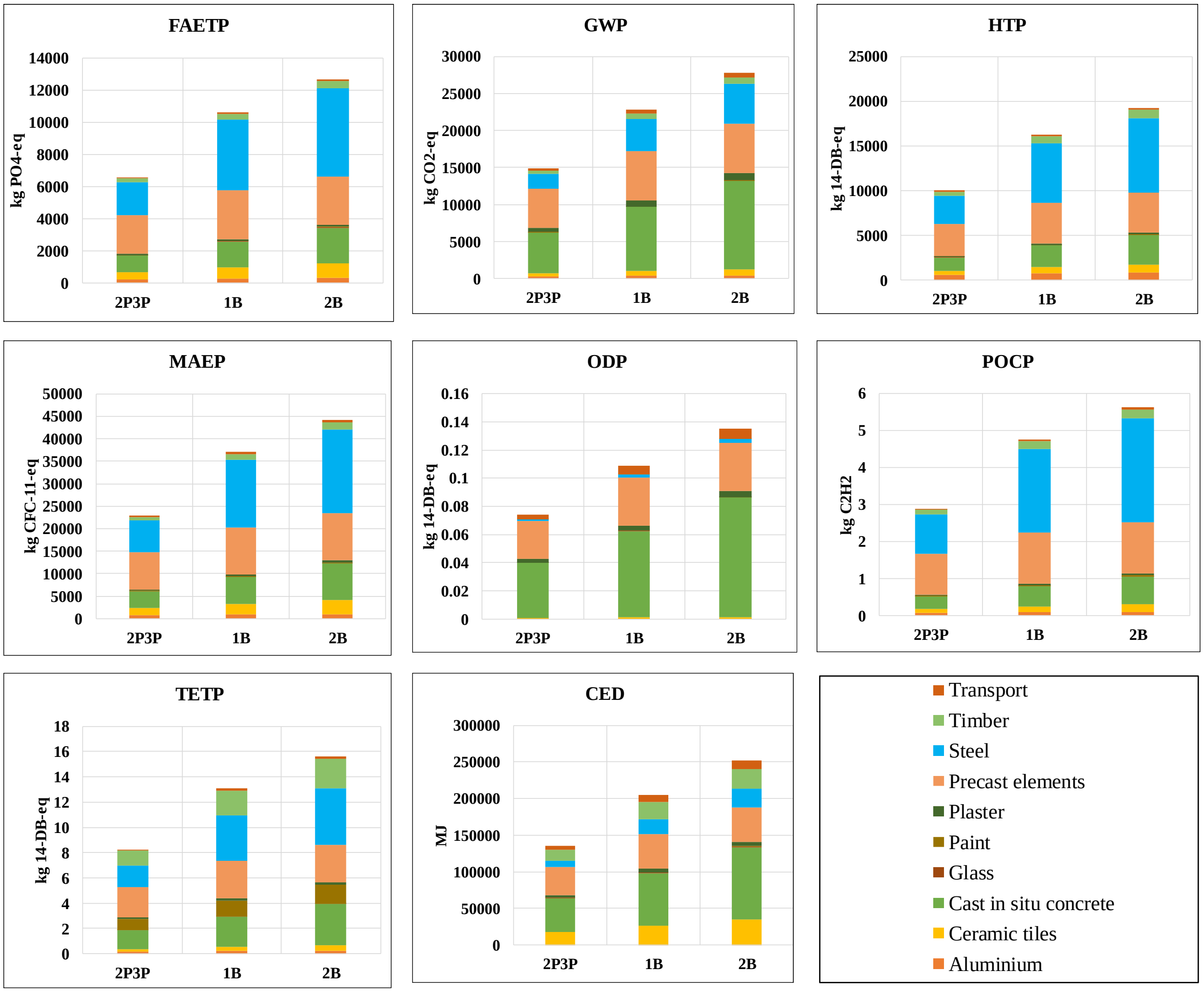


Fig. 8. Embodied impacts at flat levels

3.4. Embodied impacts at assembly levels

Public residential buildings in Hong Kong use precast assemblies including façades, bathroom pods, kitchen pods, refuse chutes and water tanks. Therefore, the developed method automates embodied impact at these levels as well. Fig. 9 shows the embodied impacts of four assemblies which is evaluated per unit of each assembly for standardized bathroom pods, kitchen pods, and refuse chutes, whereas that for the façade is an average value as more than one façade type is used in the case building. Refuse chute has the lowest impact on GWP and CED (1179.94 kg CO_2 and 13.39 GJ), followed by façades (1408.58 kg CO_2 and 14.96GJ), bathroom pods (1735.44 kg CO_2 and 17.67 GJ) and kitchen pods (3653.55 kg CO_2 and 37.21). The results for other impact categories are also illustrated in Fig. 8. In addition, impacts per material are evaluated to elucidate main contributors to production and transportation phases. Concrete, steel, and aluminum (façade only) are identified as hotspots which totally contribute from 84% to 89% in all assemblies. The remaining 11% to 16% is attributed to manufacturing and transportation.

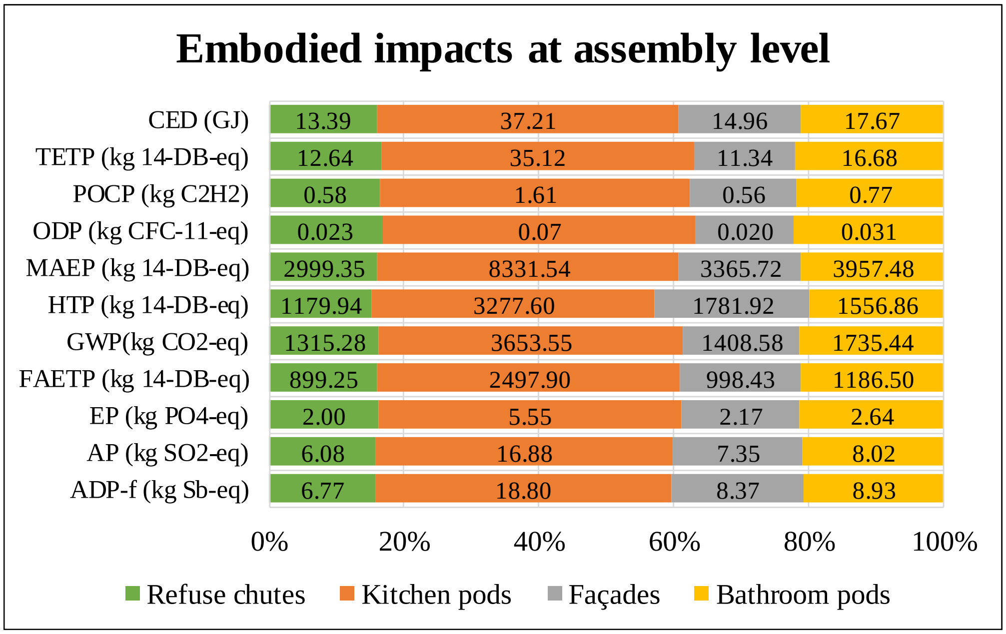


Fig. 9. Embodied impacts at assembly levels

3.5. Embodied impacts at component level

Fig. 10. illustrates the contribution of each building element to the life cycle impact of the case building. A cradle to end-of-life analysis is performed in this level for the studied impact categories. Similar trends of contributions from different components are observed for all impact categories except HTP, OPD and TETP. The contribution of walls prevails in all impact categories (ranging from 18.40% to 38.87%) except in TETP where the contribution of doors dominates (36.47%). Next to walls, floor slabs contribute significantly to all impact categories ranging from 22.36% to 37.48%. Contributions of other structural framing components such as beams, and columns are between 7.43% and 12.14% and 9.36% and 16.78%, respectively. Openings including doors and windows also make significant contributions ranging from 0.62% to 36.47% and 0.12% to 9.40% respectively due to the use of timber and aluminum. These results are consistent with the component contribution ranges reported in (Morales et al., 2019). For the purpose of comparison between components, the contribution to GWP and CED from different components is presented as: walls (36.34% and 35.89%), floor (23.96% and 24.25%), columns (16.20% and 15.90%), beams (11.15% and 10.84%), doors (7.58% and 7.84%), windows (3.24% and 3.36%), stairs (0.81% and 0.83%), roof (0.84% and 0.92%) and refuse chute (0.14% and 0.15%).

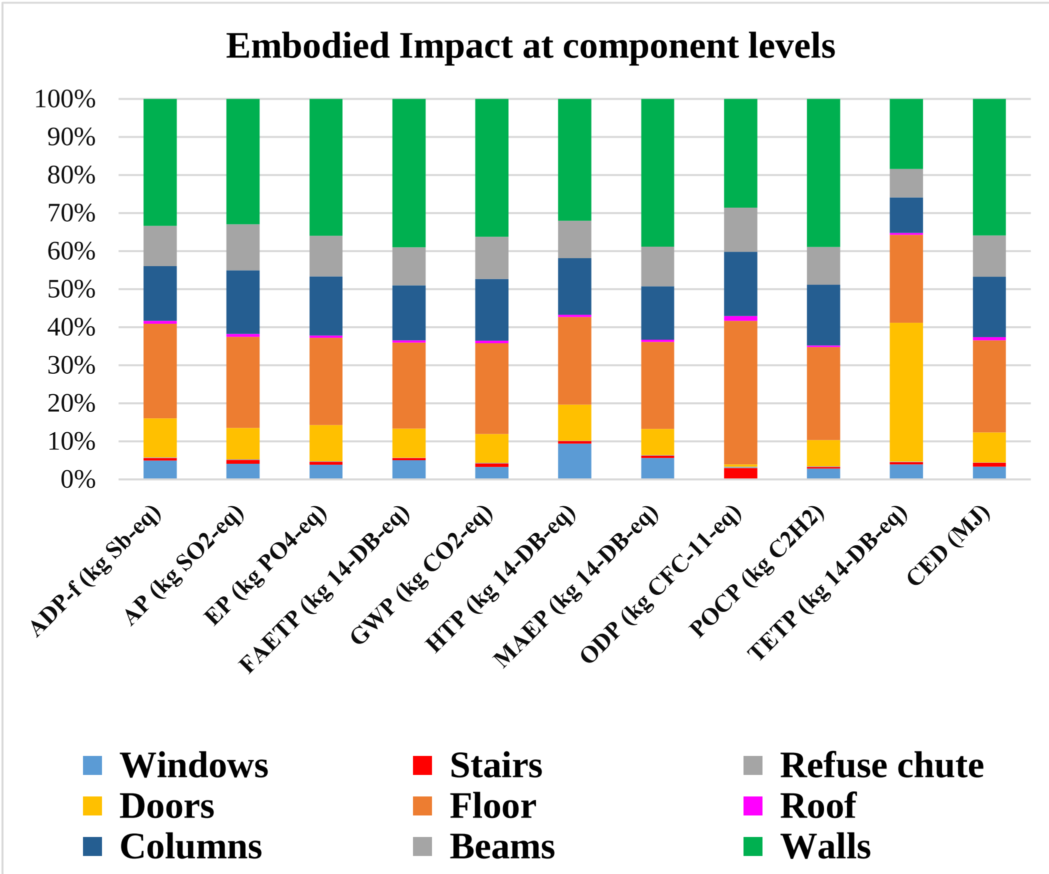


Fig. 10. Embodied impacts at component levels

3.6. Operational impact of the building

The operational impacts of the case building are calculated based on operational schedules presented in (Yu et al., 2019). Within the assumed 50 years lifespan, the CED for cooling, cooking, daily hot water, lighting, and other appliances is equivalent to 22.24 GJ/m^2 (i.e. 6177 kWh/m^2). The mean annual operational energy use for cooling, cooking, daily hot water, lighting, and other appliances is 45.09 kWh/m^2, 26.56 kWh/m^2, 22.61 kWh/m^2, 7.04 kWh/m^2 and 22.24 kWh/m^2 respectively. These results are consistent with the reported energy use of a public residential building in Hong Kong with an average energy use intensity of 106.6 kWh/m^2 (Qin and Pan, 2020). The operational impacts for other considered indicators are calculated based on Hong Kong's fuel mix as shown in Fig. 11. Similar distribution patterns of contributions are observed for all indicators except ODP. Particularly, cooking shows a less impact in GWP, TETP, POCP, FAETP, EP, AP, and HTP, as natural gas production is much cleaner than electricity production for Hong Kong's fuel mix. Hence, it is more environment-friendly if daily hot water demands are met with natural gas.

From a lifecycle perspective, the operational phase has the greatest impact on the environment. The total CED and GWP of the case building is 30.22 GJ/m^2 and 4141.70 kg CO_2 eq, where the operation phase accounts for 73.57% of CED and 84.49% of GWP. These results are in line with the ranges estimated by (Chau et al., 2015). Due to the long period of the operational phase, it accounts for a larger portion of the life cycle impacts. However, great opportunities are perceived in integrating renewable energy technologies into façades of high-rise buildings to significantly reduce both operational and embodied impacts.

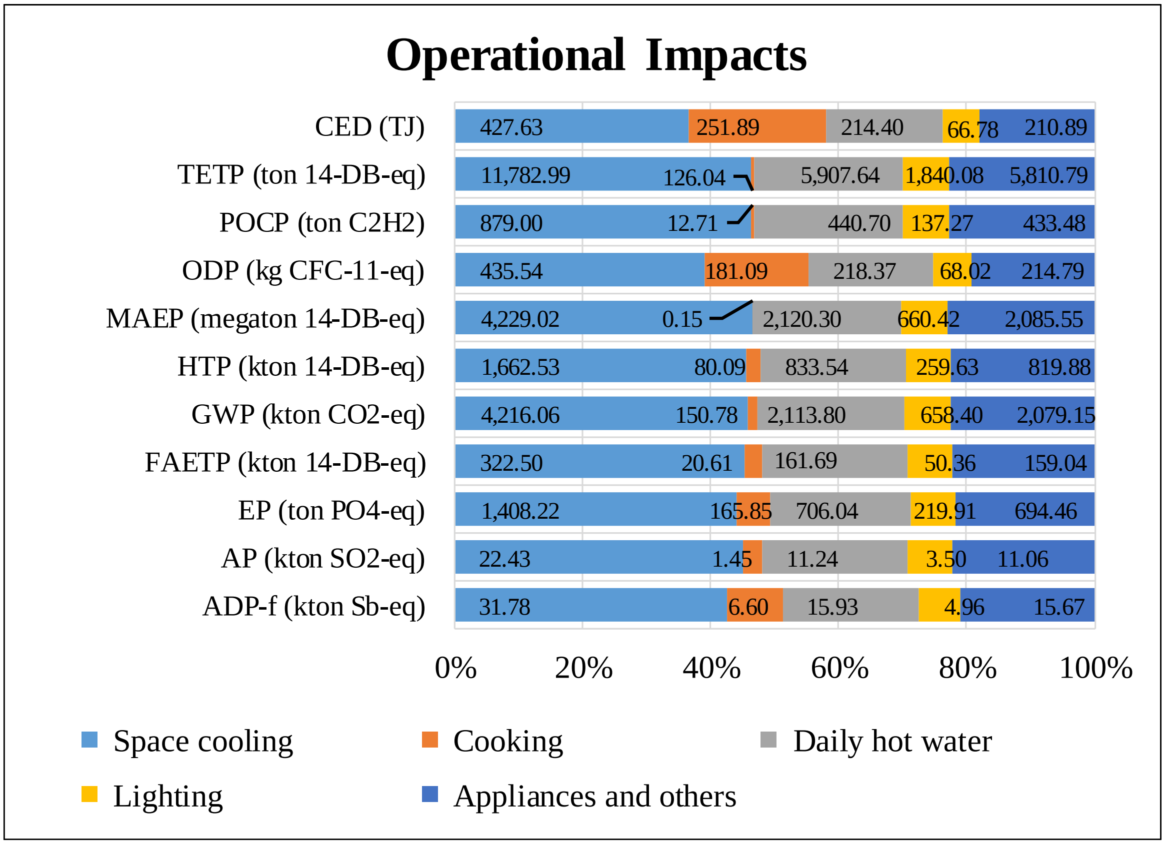


Fig. 11. Operational impacts of case building

4. Discussion

Given limitations in existing BIM-based LCA methodologies for prefabricated buildings, this study developed a BIM-based LCA method for automatic and comprehensive assessments of prefabricated buildings which was validated through a case study on a typical prefabricated residential building in Hong Kong. The developed tool provides several benefits in comparison to existing BIM-based LCA tools.

This method automates a systematic result at different levels of assessments which has been ignored in previous studies. Considering that standardized components are used in prefabricated buildings, it was necessary to align the developed tool with systematic LCA frameworks such as (Teng and Pan, 2019). Accordingly, more detailed, and comparable LCA results are automatically produced allowing for deep analyses and identifications of hotspots including the best combination of components such as façades, bathroom/kitchen pods or even flats in modular designs. For instance, through this method, the one-bedroom flat is identified as the best performing flat type in comparison with other flats in the case building. Such characterization provides insight to design optimization of prefabricated buildings.

Furthermore, investigating a broader scope of lifecycle phases leads to a more comprehensive lifecycle profile which has not been achieved in previous BIM-based LCA studies. Particularly, improvements in the evaluation of transportation, construction and end-of-life phases have been achieved with an enhanced database and its integration with BIM to allocate transport modes, load factors, construction and demolition equipment. Although transportation distances are currently included in the database, map applications can be integrated into the process with prospects of optimizing transportation distances. In addition, the developed method includes equipment uses in the construction phase and can therefore enhance the estimation of construction impact which has been a major blind spot in previous studies. In the future, more details may be included for other equipment used during the construction phase as a supplement to the current equipment list. The flexibility to select different impact assessment methods in the new approach also enhances its applicability to other regions where miscellaneous performance indicators other than the energy use may be of interest. The results presented in the analysis covered energy and a wide range of environmental impacts which have been ignored in most previous studies.

In this study, general assumptions from existing literatures and Ecoinvent have been adopted for developing the database. However, evolving construction processes and technologies could result in different impact levels which can be resolved through primary data collections from experts. Particularly, the collection of real operational data such as used equipment, fuel consumption and operation times during the construction of a typical prefabricated project could improve the evaluation accuracy of the construction phase. For the end-of-life phase, diverse management strategies can be explored for a more comprehensive assessment subject to the inclusion of more strategies in the database and enhancing the developed method for such applications. Presently, only recycling benefits of reinforcement bars are considered. If recycling is excluded from the tool, the embodied impacts of the end of life phases could be much higher as steel is one of the most influential materials.

However, some limitations are identified in bridging gaps between structural and architectural domains of the model. For elements such as columns, significant challenges are identified in coordinating structural elements in reinforcement and finishes (e.g. plaster and paints). Although their impacts could be easily eliminated in a one-off modeling, it could be a significant challenge during repeated design iterations.

Another significant challenge exists in applying the developed method to building service components. Most components such as ducts are treated as solids instead of hollow units which could result in large errors. Two potential solutions are proposed in such situations: estimating an average value based on a parameter of ducts or assessing impacts at aggregated levels (components) rather than specific materials.

Finally, a comparative analysis of residential buildings in Hong Kong is presented in terms of GWP as most existing studies use this indicator. The assessment results, scopes and deviations are presented in Table 5. Significant deviations are observed among studies due to variations in system boundaries and LCIA data. For instance, the results of (Gan et al., 2017) indicate an underestimation of 22.59% in GHG emissions as only principal structural material were considered in their study. Although the study is consistent with the finding in (Teng and Pan, 2019), the overall LCA impacts is found to be higher due to the expanded system boundaries. Thus, if the system boundaries are adjusted the results are likely to very similar to the present study.

Table 5. Comparative analysis of residential buildings in Hong Kong

Study	**System boundary**	**kg CO_2 eq/m^2·y**	**LCIA data**	**Deviation**
Present study	Cradle to end-of-life	12.84	Localized	-
(Hossain and Ng, 2020)	Cradle to end-of-life	13.82	Localized	7.63%
		11.86	Generic	-7.63%
(Teng and Pan, 2019)	Cradle to end of construction	11.22	Localized	-12.62%
(Gan et al., 2017)	Cradle to site	9.94	Localized	-22.59%
(Dong and Ng, 2015)	Cradle to end of construction	12.74	Generic	-0.78%
(Dong et al., 2015)	cradle-to-end of construction	13.38	Generic	4.21%

5. Conclusions

This study developed a BIM-based LCA method to evaluate the life cycle energy and environmental impacts of prefabricated buildings. This approach is based on a more standardized levels of assessments, a broader scope of lifecycle phases, and more comprehensive functional units and system boundaries. The unique characteristics of prefabricated LCA including transportation and construction modalities have also been addressed to automate the lifecycle process with high accuracy.

The method has been successfully tested on a typical prefabricated high-rise building in Hong Kong and proven to produce accurate results with a higher computational efficiency for different levels of assessments, system boundaries and functional units comparable with previous studies. It is achieved through an automated process of systematic zoning and set up after creating parameters and populating BIM with LCA data. The total CED and GWP of the case building are estimated to be 30.22 GJ/m^2 and 4141.70 kgCO_2eq, respectively. Also, the operational CED and GWP are estimated to be 22.24 GJ/m^2 and 3499.30 kgCO_2eq respectively while embodied CED and GWP are 7.99 GJ and 642.40 kg CO_2 eq respectively. Embodied impacts at flat levels are estimated to be 134,984.17 MJ and 14,935.95 kg CO_2 for Flat 2P3P, 193,204.56 MJ and 21,190.32 kg CO_2 for Flat 1B and 252,194.74 MJ and 27,818.07 kg CO_2 for Flat 2B. Therefore, Flat 1B is proved to be the most sustainable design given its lowest lifecycle impact. In addition, kitchen pods and walls are found with the highest impact in their corresponding assessment levels.

The detailed levels of assessments addressed as well as automation and computational efficiency achieved will provide an enhanced mechanism to iterate design options at materials, element, assembly, or flat levels to evaluate energy and environmental management opportunities in future studies. Moreover, the designed assessment levels can be easily manipulated to reflect other geographical or prefabrication systems. The study is particularly useful for building practitioners to swiftly evaluate the lifecycle impact of prefabricated buildings with deep insights. Also, the research finding can guide design optimizations of low-carbon building constructions and renovations.

Nonetheless, additional efforts are needed for a complete representation of the lifecycle profile. The study has considered varying system boundaries from cradle to end-of-life phases, however a wider range of end-of-life management strategies could be integrated for more comprehensive assessments. Also, the method did not include the embodied impacts of building service systems as significant challenges are faced in the extraction and processing of materials used in some of these components. In future studies, these limitations will be addressed. The method will be further incorporated into extensive sensitivity and uncertainty analyses for a robust life-cycle design optimization.

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