Integration of BIM and LCA: a system to predict and optimise embodied carbon for prefabricated buildings

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ABSTRACT

This paper presents the development of a system for automatically predicting and optimising embodied carbon of prefabricated buildings during the design phase. Building information modelling (BIM) is selected as the working environment from data input to results display, highly improving the automation level of carbon assessment. Besides, automatic carbon assessment for on-site installation is achieved by developing a component-oriented on-site emission factor database from a Chinese code. This system also supports optimising embodied carbon by providing various low-carbon alternatives from the perspectives of selecting construction materials, transportation modes, and installation methods. This system is applied to a ten-storey office building for demonstration. It is found that the system can accurately estimate and efficiently reduce the embodied carbon emissions of prefabricated buildings.

KEYWORDS Embodied carbon; life cycle assessment; optimisation; building information model; prefabricated building
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1. Introduction

With natural disasters occurring with increasing frequency and the growing danger that Greenhouse Gases (GHGs) pose to the environment and humans, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), the three most important GHGs, are gaining greater attention around the world. According to the Fifth Assessment Report (AR5) by Intergovernmental Panel on Climate Change (IPCC) (Meyer et al., 2015), CO_2 has become regarded as the main contributor to the anthropogenic radiative forcing since 1750 in relation to the fastest-increasing decadal rate of concentrations in the Earth's atmosphere. An estimated 49 gross tonnage (Gt) of CO_2 is emitted into the natural environment each year as a result of human activities, and the building sector accounts for 25% of the total emissions (Edenhofer et al., 2015), which also means that buildings have great potential to help alleviate the tremendous pressure brought by environmental problems. Many governments have set commitments to limit carbon emissions to improve the ecological environment, and the Hong Kong Special Administrative Region (HKSAR) has also promised to achieve carbon neutrality by 2050 by way of sustainable development. As a response, plenty of scholars and researchers have developed various approaches to measure and minimise the carbon emissions from building projects. Praseeda et al. (2016) classified the emissions during the building life into embodied, operating, maintenance, and demolition emissions. 73 cases, including residential and commercial buildings, were studied by Ramesh et al. (2011), who concluded that a building's operating and embodied emissions are the main contributors to its overall amount thereof. Embodied carbon (EC) exists in many different procedures like manufacturing, shipping, and construction, and operating carbon (OC), on the other hand, mainly arises from the energy consumption in operating buildings. OC represents about 80% of the total, while EC only accounts for 20%. Therefore, the most pertinent papers have concentrated on reducing OC emissions, and many advanced technologies have already been applied in the field. Photovoltaic panels are a typical cleaning strategy to replace electricity with solar energy, thereby reducing operating carbon emissions and achieving self-sufficient buildings. With these innovative solutions applied to modern buildings, EC emissions share a higher percentage of the total in low-energy buildings than conventional buildings and are unignorable (Thormark, 2002). Chau et al. (2015) divided the definition of EC into two categories:

(1) Initial EC, which reflects the energy expended in material, transportation, and installation phases; and
(2) Recurring EC, which corresponds to the maintenance and repair during the operational phase. However, this paper excludes recurring EC from consideration because of the significant uncertainties caused by the uniqueness of buildings and the fact that it cannot be forecast at the design stage.

In order to evaluate a building's carbon emissions, the most widely selected method is life cycle assessment (LCA), which estimates the emissions during the lifespan of a building. As the system boundary defined in EN 15978, the burdens and benefits beyond the building's service life (i.e., Module D) are also considered for LCA. Depending on the objects to be assessed, the LCA process can be broadly divided into three sub-methods: Input-Output (I-O) analysis, process analysis, and hybrid analysis. Typically, I-O analysis is applied to assess districts containing multiple buildings, while process analysis is suitable for single construction. Nässén et al. (2007) compared the energy use and CO_2 emissions of Swedish buildings between I-O and process analysis and explained the differences by considering the truncation errors of boundary definition in the latter method. A building sector in China was quantified through the hybrid method, which overcame the limitation of the system boundary and improved the calculation's reliability (Zhang and Wang, 2016). Considering that a single building is the main object, this study adopts process LCA (P-LCA) to evaluate the EC.

Traditionally, LCA is conducted in Excel or specialised software (e.g. SimaPro), which is always time-consuming. Building information modelling (BIM) technologies have dramatically developed and have been widely applied in the construction industry in the past decades. According to the National Institute of Building Sciences (NIBS), BIM digitally presents physical and functional characteristics. In a narrow interpretation, BIM is usually regarded as the construction design process through digital modelling technologies. In a broad interpretation, the definition of BIM extends beyond the 3D model and incorporates 4D and 5D (i.e. time and cost). Sometimes, the scope can be expanded to include other analyses, like LCA. Thanks to sufficient information and the powerful arithmetic functionality provided by BIM, the efficiency of LCA can be highly improved. However, there are still gaps in the current BIM-LCA research. Therefore, the rest of this paper is organised as follows:

(1) after a literature review of previous BIM–LCA research, the objectives are proposed based on the gaps identified in past studies;
(2) a methodology for developing a BIM–LCA tool is introduced;
(3) a calculator is applied to a building model to test the applicability;
(4) the results are discussed for validity verification and proof of carbon optimisation; and
(5) conclusions are presented and future work suggested.

2. Literature review and objectives

2.1. State of the art

Regarding integrating BIM and LCA, Wastiels and Decupere (2019) classified the existing tools into five types. In the first type, BIM is only a quantity takeoff tool, and the subsequent LCA steps take place within dedicated LCA software. In replace of the Bill of Quantity (BoQ), the Industry Foundation Class (IFC) file is the medium containing various BIM information (e.g. material quantity, project's globally unique identifier [GUID]) in the second type. After exporting the building model, the third type introduces BIM viewers (e.g. BIMcollab Zoom) before the import to LCA software. This enables designers to input related LCA properties in a 3D environment rather than in LCA software, which is typically a 2D interface. Unlike the first three types, the fourth type allows designers to conduct LCA only in the BIM software through a plug-in. The last type incorporates LCA data into the BIM environment via secondary development, which is associated with other functional information (e.g. geometry) in the BIM model. This supports real-time updates of LCA data after the building elements are changed.

After reviewing 60 BIM-LCA studies, Potrč Obrecht et al. (2020) found that 60% fell into the first type, with 20% not being classified. A similar conclusion (i.e., exporting BoQ from BIM is the primary integration method between BIM and LCA) was drawn by Tam et al., (2022) based on a critical review of 61 relevant papers from 2012–2021. From a technical point of view, Potrč Obrecht et al. (2020) also evaluated the automation level of data exchange between BIM and LCA and pointed out that 83% of studies require totally or partly manual operation in terms of the link between BIM and LCA. Most of this 83% falls into the first three types (Potrč Obrecht et al., 2020), which all require switching between multiple software. On the contrary, Type 4 and Type 5 enable the whole LCA process within a single software package, dramatically improving work efficiency and reducing error possibility. From an LCA view, Potrč Obrecht et al., (2020) identified that more than half of studies adopt the whole building as the assessment unit and normalise environmental impact by dividing it by the total floor area. In terms of the system boundary, the transportation and construction stages are omitted from 40% and 70% of studies, respectively for initial EC estimation (Potrč Obrecht et al., 2020). This perspective is echoed by Nizam et al., (2018), who indicated that the estimation of construction work is ignored in seven of 11 reviewed BIM–LCA tools. To eliminate the technical shortcomings of Types 1, 2, and 3, only BIM–LCA tools belonging to either Type 4 or Type 5 are reviewed in the following, from both technical and LCA perspectives.

In Type 4, BIM plug-ins serve as the environment for conducting LCA. Nizam et al. (2018) developed a Revit plug-in combining various functions to estimate embodied energy consumption, from extracting data to showing the LCA results. Although this plug-in embeds databases to improve the automation level, it still requires manual selection and assignment of LCA data to each building component. In addition, it does not support the comparison between different design cases in the BIM environment, which means that users need to export the LCA results to other software (e.g. Excel) for comparison. In terms of the LCA perspective, this calculator considers the transportation and construction stages besides the production stage. Compared with the research by Nizam et al. (2018), the plug-in developed by Kamari et al. (2022) highly improves the automation level, which performs the mapping and calculation process only with one click. However, this tool is only used for environmental impact estimation, not for comparison and optimisation purposes. Besides, the system boundary adopted by this tool only includes the production stage. Like Kamari et al., Santo et al. (2019) excluded the transportation and construction phases when developing a Revit plug-in for LCA and life cycle costing (LCC) estimation. After further development, this plug-in includes these two and even other phases (i.e. operational and end-of-life) (Santos et al., 2020). However, its automation level is reduced by manual attribution of LCA or LCC parameters. Carbon comparison and optimisation are also not allowed in this tool. Like the research above, the plug-in developed by Lee et al. (2015) does not support comparison and optimisation of environmental impact either, despite a whole life cycle system boundary being declared. Beyond academic research, Tally and OneClickLCA are two popular commercial Revit plug-ins for LCA. Tally's main LCA data source is the GaBi and US LCA databases, while OneClickLCA is based on hundreds of environment product declarations (EPDs). Regarding the system boundary, Tally (2017) estimates the environmental impact of the transportation stage based on a commodity flow survey by the US government and excludes the construction stage. OneClickLCA has not been tested due to the licensing problem. Compared with BIM–LCA tools in academic papers, Tally demonstrates better performance in regard to software's systematic and operational nature. Moreover, it allows users to create a benchmark and compare different design strategies. However, to ensure the generality of the software, the automation level is decreased as it requires manual selection and attribution of the LCA data for each building element.

In Type 5, the LCA data are directly defined in BIM models and associated with other functional information (e.g. geometry). Dynamo, a parametric modelling tool embedded in Revit, was used by Röck et al. (2017) to process the integration of BIM and LCA. Based on Swiss SIA MB 2032, this framework estimates the global warming potentials (GWPs) of every building component in multiple construction scenarios and then visualises the results in BIM models. This can help designers identify which component has more potential to reduce the environmental impact in the following design. The data exchange between BIM and LCA is fully automated through a common name convention. However, this tool only applies to the conceptual design stage before material assignments. Unlike Röck, Schwartz et al. (2016) proposed a workflow linking EPDs and BIM through IFC files. By reconstructing the structure of EPD information, Schwartz et al. successfully integrated EPD data into IFC files and finally displayed the LCA results in Revit. However, only the production stage is considered in this framework, and no prototype has been developed to show the applicability.

The identified gaps can be classified into technical and LCA issues. From a technical perspective, most BIM–LCA studies still regard BIM only as a quantity takeoff tool so far (Potrč Obrecht et al., 2020; Tam et al., 2022). However, it is also worth noting that there has been more research focusing on developing tools (Kamari et al., 2022; Lee et al., 2015; Nizam et al., 2018; Röck et al., 2017; Santos et al., 2019; Santos et al., 2020; Schwartz et al., 2016) to allow the entire LCA process (i.e., from data input to results display) totally in the BIM environment in recent years. Moreover, most BIM–LCA tools still depend on manual operation for the data exchange between BIM and LCA (Nizam et al., 2018; Potrč Obrecht et al., 2020; Santos et al., 2019; Santos et al., 2020). Therefore, the automation level is waiting to be improved. From an LCA perspective, most BIM–LCA tools focus on the production stage, easily omitting the transportation and construction stages for initial EC estimation (Kamari et al., 2022; Nizam et al., 2018; Potrč Obrecht et al., 2020; Schwartz et al., 2016). Even though some tools (Santos et al., 2020; Tally, 2017) include transit and on-site work, they still require detailed information input (e.g. on-site energy estimation) during the LCA. However, this information is difficult to predict in the building design stage, where BIM is most often applied. Furthermore, few academic studies support carbon comparison and optimisation in the BIM environment (Kamari et al., 2022; Lee at al., 2015; Nizam et al., 2018; Santos et al., 2019; Santos et al., 2020). This gap is also identified in review papers by Xue et al. (2021) and Safari and AzariJafari (2021).

2.2. Objectives

This paper aims to present the development of an EC calculator that enables users to conduct BIM and LCA using a single software package. Autodesk Revit is the most popular software worldwide for building information modelling. Therefore, a Revit plug-in (i.e. Type 4) is the best integration strategy between BIM and LCA for this paper. Furthermore, to improve the automation level of data exchange between BIM and LCA, the same naming convention is applied for modelling the building and constructing the LCA database. In this case, the LCA data are automatically attributed to the building elements during the calculation, which reduces time consumption and the possibility of making mistakes. Moreover, the plug-in's user interface is designed to improve the automation level by providing default values and reducing user interactions.

Regarding the LCA consideration, all the stages (i.e. the production, transportation, and construction stages) for initial EC estimation are included in this Revit plug-in. However, assessing the environmental impact on the construction site is difficult as significant variations exist between different projects. This is always the reason why researchers exclude construction work from consideration. But with the introduction and prevalence of the prefabrication method, the on-site work is simplified and standardised. Therefore, this paper selects prefabricated building projects as the assessment object to incorporate the construction stage in LCA. In addition, this Revit plug-in is expected to support carbon optimisation after estimation, which is achieved by replacing the original design with low-carbon alternatives. After reviewing 102 articles and identifying 17 strategies, Pomponi and Moncaster (2016)

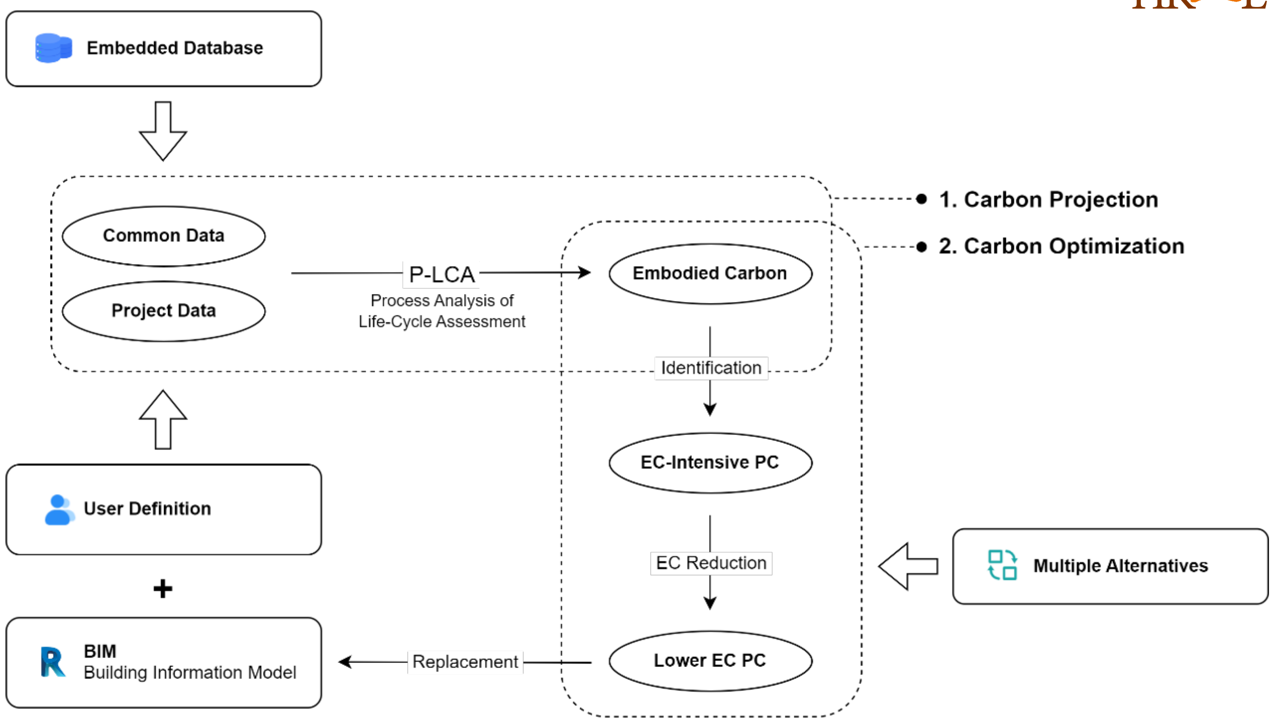


Figure 1. Overall workflow.

revealed that a pluralistic approach is necessary to mitigate EC effectively. Therefore, some possible low-carbon tactics will be provided in all three LCA stages.

In conclusion, a Revit plug-in is expected to be developed for the LCA of the initial EC. From the perspective of the integration of BIM and LCA, this plug-in will

(1) allow users to complete the whole LCA process only in Revit;
(2) achieve the automated data exchange between BIM and LCA; and
(3) improve the automation level of plug-in operation.

From the LCA perspective, this plug-in will

(1) include the production stage, transportation, and construction stage (i.e. Modules A1–A5 defined in EN 15978); and
(2) enable users not only to predict but also optimise the initial EC in the design stage.

3. Methodology

The workflow (Figure 1) for achieving the research purpose includes two modules: (1) carbon projection; and (2) carbon optimisation. Besides, some spreadsheet databases and various low-carbon substitutions are embedded in this BIM-based calculator for convenience.

3.1. Carbon projection

Compared with Input-Output analysis of Lift-Cycle Assessment (IO-LCA), P-LCA possesses a more straightforward computing logic for carbon estimation, which involves summing all emissions during a building's life cycle. The system boundary is a frequently debated topic in P-LCA studies as it is regarded as one of the causes of results discrepancies between similar building cases (Anand and Amor, 2017). Due to significant uncertainties in the operational and demolition stages, this study only focuses on the initial EC estimation. Therefore, the "cradle-to-construction" system boundary is adopted, incorporating production, transportation, and construction stages for predicting the initial EC emissions of prefabricated building projects.

In terms of the functional unit, many LCA studies only assess the total quantity of a building project (e.g. [Zhou, 2021]). Besides, the unit area of carbon emissions is another frequently used unit, echoed by Barhramian (2020), who found that 61% of researchers take "m^2" as the functional unit. After confirming that a considerable portion of EC comes from the material stage, Luo et al. (2019) divided the total emissions according to the material type. Dong et al. (2015) made a comparison between precast and cast-in-situ construction styles at four levels: (1) cubic metre concrete; (2) precast façade; (3) group of façade elements; and (4) apartment. In conclusion, there is no uniform unit for estimating carbon emissions, and different perspectives suit different purposes. This framework adopts the prefabricated component (PC) (e.g. beam) as the functional unit for carbon optimisation.

3.1.1. Computational framework

For prefabricated buildings in this schema, the total EC (EC_T) is equal to the sum of emissions in the precast stage (EC_P), transportation stage (EC_{TR}), and the construction stage (EC_C), as shown in the following formula:

$$EC_T = EC_P + EC_{TR} + EC_C\,. \tag{1}$$

The algorithm of all three phases can be demonstrated by one generic equation, which is also the core of P-LCA analysis. The letters A_i and f_i denote the activities of exhausting pollutants and corresponding emission factors, respectively.

$$EC = \sum_i A_i \cdot f_i\,. \tag{2}$$

First, in the production sector, building materials like concrete, steel, and brick appear to account for most EC, which is supported by a previous study (Kumanayake et al., 2018). To estimate the total EC from prefabrication, the formula below illustrates the logic for N kinds of materials, an accumulation operation. Each material's EC is the multiplied product of its mass (m_{Mi}) and emission factor (f_{Mi}):

$$EC_P = \sum_i^N m_{M_i} f_{M_i}\,. \tag{3}$$

Second, during the delivery of the PC, the EC emission is entirely from the combustion of fuel, and the consumed quantity depends on the transit distance (L_{TR}) and loading weight (m_{TR}). According to common sense, the relationship between them is a monotonically increasing function, which means that longer distances or heavier loads will lead to more emissions. An equation including these two factors is proposed where the emission factors (f_{TR}) for different transit types are also defined:

$$EC_{TR} = m_{TR} L_{TR} f_{TR}\,. \tag{4}$$

Finally, the calculation for the construction stage is more complicated than the former two since the EC emission is related to multiple resources, which can be classified into three categories: labour, on-site materials, and construction machinery. The GHG Protocol published in 2009 defined three scopes for corporations and governments to assess carbon emissions and allocate these resources into different scopes. Scope 1 is the direct emissions from fuel combustion and the enterprises' physical or chemical processes. The greenhouse gases from materials in building projects should belong to this scope. Scope 2 is the indirect emissions exhausted from the energy usually purchased from outside the enterprises, and the electricity used in non-generating power companies is a good illustration of scope 2. The on-site equipment should be categorised as the first or second scope according to its affiliated business. Scope 3 is the corporate value chain emissions, which are generally ignored for vast uncertainty and vague definition, and labour consumption is what this scope contains. In verification guidelines by ISO14064-1, the third scope is optional, so this study does not include the effects of labour on the environment. Then, EC from the PC installation should have two sections, as per the equation which follows:

$$EC_C = EC_{C,M} + EC_{C,E}\,. \tag{5}$$

The EC emissions from on-site materials ($EC_{C,M}$) share the same formula as that in the production stage. In spite of the equipment being a little more complex to estimate the EC ($EC_{C,E}$), time horizon and volumetric dimension are combined to simplify the function. For each machine type, $q_{C,Ei}$ expresses the fuel or electricity used by one machine in eight hours, and $n_{C,Ei}$ is the consumption of equipment measured by the unit of one machine in eight hours. Moreover, $f_{C,Ei}$ denotes the emission factor counterparts of gasoline, diesel, and electricity:

$$EC_{C,E} = \sum_i^N n_{C,E_i} q_{C,E_i} f_{C,E_i}\,. \tag{6}$$

3.1.2. Data collection

The data used by different stages are illustrated in Figure 2.

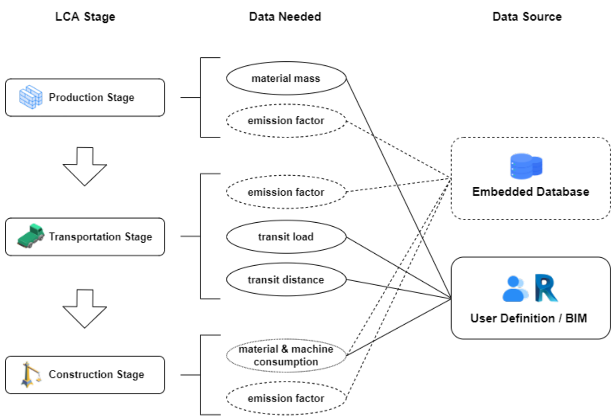


Figure 2. Data classification used by different stages.

The emission factor database should be developed and embedded in this Revit plug-in for LCA data. In the light of different stages, the emission factor has different connotations, which can be divided into three typologies: (1) for materials; (2) for transit types; and (3) for machinery types. The units in correspondence with them are (1) "CO_2e *kg/t* "; (2) "CO_2e *kg/(t • km)* "; and (3) "CO_2e *kg/kWh* " or "CO_2e *kg/kg* ". Some institutions have tried to build databases related to the environmental impact of buildings. Ecoinvent and GaBi are the two most widely used LCA databases worldwide. Typically, they are the first choice for manufacturers to generate EPDs. However, this paper abandons them for financial reasons. In terms of the free LCA database, the Inventory of Carbon and Energy (ICE) (Hammond and Jones, 2008) is normally adopted by scholars. It was developed from various resources, including academic research, government publications, and other LCA databases, like Athena's. The ICE 3.0 repository covered over 400 building materials and some miscellaneous items. Therefore, it is the best choice for materials' emission factors. In addition, the GBT 51366-2019 (2019) offers emission factors for common transportation and on-site equipment in the Chinese context so that it can be used for the latter two databases.

For BIM data, engineering quantities of the production and transportation stages can be easily derived from the BIM model, while the consumption of materials and machines on site is hard to estimate. The primary site work for prefabricated buildings is PC assembly, which can be easily broken down into several standard streamlined steps, like lifting, underpinning, and connection. Regardless of the structure or building function, this procedure is appropriate for all prefabricated buildings, making quota allocation possible. Another Chinese code (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2015) formulates the quotas for labour, material, and equipment usage for prefabricated buildings and applies them to cost analysis. This study draws on this code to propose an on-site EC quota framework, addressing the most challenging part of the whole life cycle evaluation. All the materials and machines used in the installation procedure are allocated to each PC according to different categories, including beam, column, wall, and floor. Eventually, every PC has been assigned a "cradle-to-construction" life cycle EC, waiting for the subsequent step-carbon optimisation.

3.2. Carbon optimisation

The core principle of carbon optimisation is optimising the EC from manufacturing to the end of construction with multiple lower-emission solutions. The preliminary assessment is always the foundation to establish a benchmark for later comparison. Therefore, this carbon optimisation structure will start with an overall evaluation and identification of PCs accounting for higher percentages.

Multiple solutions are provided after the carbon identification, involving four aspects: (1) building material; (2) precast factory; (3) shipping type; and (4) on-site machinery. Engineers and stakeholders can utilise multiple strategies to effectively reduce EC, echoing the research results by Pomponi and Moncaster (2016). For building material alternatives, this paper can show users what materials contribute the most carbon emissions for the selected PC type. The material library will be linked to allow the substitution of low-carbon materials. For the transportation phase, shipping distance and type determine EC emissions simultaneously, so we provide two dimensions to relieve the environmental burden. First, prefabricated factories (2017) accepted by the Buildings Department of the HKSAR Government are marked on the Baidu Map for user selection. Second, a bound drop-down list of 15 transit vehicles allows customers to apply various modes. Combining manufacturing plants and transit types is flexible and more conducive to EC optimisation. Although each PC had individual materials and equipment allotted during construction, more than 30 machines are bound in a combination box for replacement. The building designers can substitute the original settings with more sustainable devices.

After confirming the substitution choices, the BIM model is automatically updated with the alternative data, and new EC results are shown. This allows users to check the difference directly in the BIM environment rather than export results to Excel and compare them. In this highly efficient way, users can reduce EC quickly.

4. Case study

A case study was conducted to test the applicability of this developed tool using the BIM model in Figure 3. Reinforced concrete and steel comprise the structural frame of this ten-storey building. Besides, it consists of 17 precast elements, complying with streamlined work (i.e. manufacturing, shipping, and assembly).

For carbon calculation, the preliminary starting and ending points for transporting PCs are The Chinese University of Hong Kong, Shenzhen and The Hong Kong University of Science and Technology, Guangzhou. The shipping vehicle is set up as a light-duty petrol van with a 2t loading capacity. The comprehensive computation results, including EC in each phase for each PC, are displayed in a table format like Figure 4. Users can filter one specific type of component or select several components to check their carbon emissions, like Figure 5.

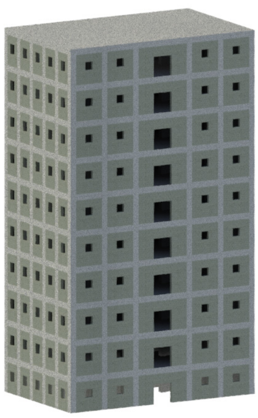
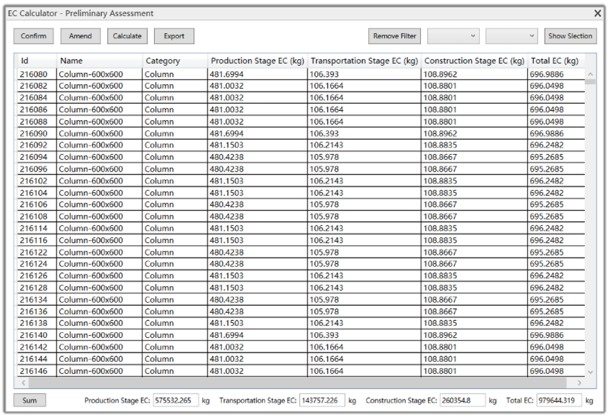


Figure 3. The ten-storey building used for the case study.



Id	Name	Category	Production Stage EC (kg)	Transportation Stage EC (kg)	Construction Stage EC (kg)	Total EC (kg)
216080	Column-600x600	Column	481.6994	106.393	108.8962	696.9886
216082	Column-600x600	Column	481.0032	106.1664	108.8801	696.0498
216084	Column-600x600	Column	481.0032	106.1664	108.8801	696.0498
216086	Column-600x600	Column	481.0032	106.1664	108.8801	696.0498
216088	Column-600x600	Column	481.0032	106.1664	108.8801	696.0498
216090	Column-600x600	Column	481.6994	106.393	108.8962	696.9886
216092	Column-600x600	Column	481.1503	106.2143	108.8835	696.2482
216094	Column-600x600	Column	480.4238	105.978	108.8667	695.2685
216096	Column-600x600	Column	480.4238	105.978	108.8667	695.2685
216102	Column-600x600	Column	481.1503	106.2143	108.8835	696.2482
216104	Column-600x600	Column	481.1503	106.2143	108.8835	696.2482
216106	Column-600x600	Column	480.4238	105.978	108.8667	695.2685
216108	Column-600x600	Column	480.4238	105.978	108.8667	695.2685
216114	Column-600x600	Column	481.1503	106.2143	108.8835	696.2482
216116	Column-600x600	Column	481.1503	106.2143	108.8835	696.2482
216122	Column-600x600	Column	480.4238	105.978	108.8667	695.2685
216124	Column-600x600	Column	480.4238	105.978	108.8667	695.2685
216126	Column-600x600	Column	481.1503	106.2143	108.8835	696.2482
216128	Column-600x600	Column	481.1503	106.2143	108.8835	696.2482
216134	Column-600x600	Column	480.4238	105.978	108.8667	695.2685
216136	Column-600x600	Column	480.4238	105.978	108.8667	695.2685
216138	Column-600x600	Column	481.1503	106.2143	108.8835	696.2482
216140	Column-600x600	Column	481.6994	106.393	108.8962	696.9886
216142	Column-600x600	Column	481.0032	106.1664	108.8801	696.0498
216144	Column-600x600	Column	481.0032	106.1664	108.8801	696.0498
216146	Column-600x600	Column	481.0032	106.1664	108.8801	696.0498

Figure 4. The computation results including EC in each phase for each PC.

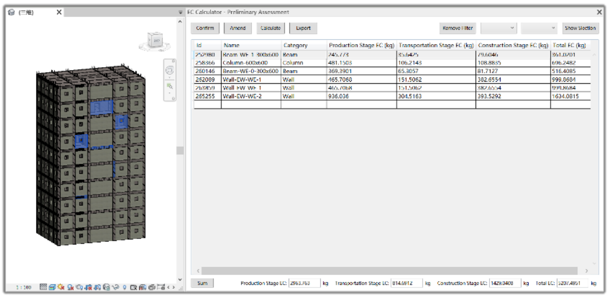


Figure 5. The filter of specific types of components or components of interest.

A graphical chart with percentage property follows to visualise the total EC distribution, assisting users to distinguish which PCs contribute more carbon emissions. For users' selection, we provide two formats, pie and bar (Figure 6). Moreover, each bar (or slice in the pie) is bound with a mouse click event to display the PC profile, showing basic information like name, quantity, and carbon amount.

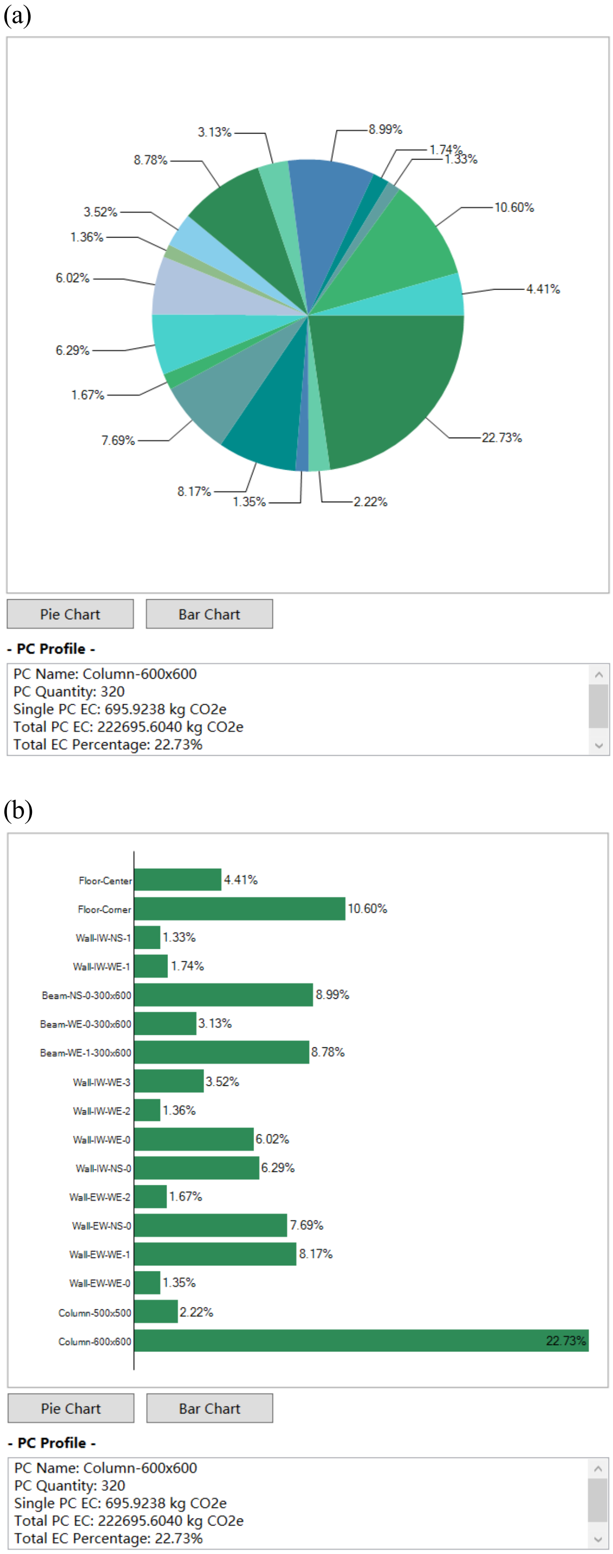


Figure 6. Graphical charts showing EC distributions.

In the same interface, more detailed emission data in the three LCA stages are displayed for EC optimisation after button clicking (Figure 7). In the panel named "production stage", for example, the selected PC's volume, mass, and material details are given. As a result, the entire EC is decomposed layer by layer, starting at the PC level and moving down through the LCA phase level to the material and equipment level. All the information is like an invisible tree, allowing users to find what they need following the branches. The production stage links with the Revit material library for alternative substitution. Production factories approved by the Hong Kong Building Department are marked on the Baidu map for possible replacement. More than 30 machines are bound in a combination box as feasible alternatives. The building designers can substitute the original settings with more sustainable devices by selecting from the combo box and clicking "Ok". As Figure 7 shows, there is a "Replace" button for every LCA step to complete the substitution automatically after alternatives. Then, new carbon emissions are calculated. After carbon optimisation, corresponding data are revised and added to the BIM environment. In the production phase, the newly selected low-carbon materials are automatically applied to the BIM model after button clicking, superseding the previous definitions.

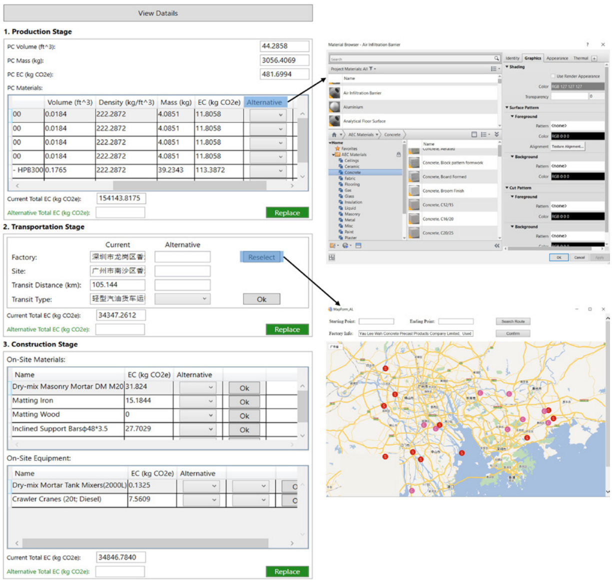


Figure 7. Detailed information display for EC optimisation.

5. Results discussion

5.1. Data validity interpretation

In this section, the plug-in calculated EC results are compared with hand calculations to verify the algorithm correctness of the plug-in. For each PC, the EC discrepancy between hand and plug-in calculations is calculated in all three LCA stages, where all the errors are smaller than 0.5%, and most are zero (Table 1). Therefore, the EC results estimated by the Revit plug-in are acceptable. The main reason for EC discrepancies is that the plug-in takes the average EC value for each PC category, while hand calculation selects one specific PC. Regarding component volume, although every PC in the same category is regarded as the same in our plug-in, there might be some differences in BIM due to technical reasons. For example, the calculation volumes of corner and side columns differ in BIM because of merging with beams. As a consequence, the volume of PC selected for hand calculation may be smaller (or larger) than the average value used in the plug-in, causing EC discrepancy.

Table 1. EC discrepancy between hand and plug-in calculations.

PC name	EC discrepancy		
	Production	Transportation	Construction
Beam-NS-0-300x600	0.17%	0.30%	0.01%
Bean-WE-0-300x600	-0.25%	-0.46%	-0.03%
Beam-WE-1-300x600	-0.26%	-0.41%	-0.01%
Column-500x500	-0.04%	-0.06%	0.00%
Column-600x600	-0.17%	-0.25%	0.00%
Wall-EW-NS-0	0.00%	0.00%	0.00%
Wall-EW-WE-0	0.00%	0.00%	0.00%
Wall-EW-WE-1	0.00%	0.00%	0.00%
Wall-EW-WE-2	0.00%	0.00%	0.00%
Wall-IW-NS-0	-0.22%	-0.22%	0.00%
Wall-IW-NS-1	0.00%	0.00%	0.00%
Wall-IW-WE-0	0.28%	0.28%	0.01%
Wall-IW-WE-1	0.00%	0.00%	0.00%
Wall-IW-WE-2	0.00%	0.00%	0.00%
Wall-IW-WE-3	0.00%	0.00%	0.00%
Floor-Center	0.00%	0.00%	0.00%
Floor-Corner	0.01%	0.01%	0.00%

5.2. EC optimisation verification

Several substitution strategies are applied to the BIM model to verify the EC optimisation from cradle to the end of construction. For each PC, the replacements of low-carbon material, shipping mode, and construction equipment are implemented independently, and then the combination of these three approaches follows. To compare the difference between these replacement strategies, all PCs adopt the same substitution policies:

(1) wholly recycled concrete (CRC) for the production stage;
(2) Yau Lee Wah Concrete Precast Products Factory in Huizhou, Guangdong, and heavy-duty petrol van for the transportation stage;
(3) a 15t crawler crane for the construction stage (in replacement of a 20t crawler crane); and
(4) the combination of three separate low-carbon methods.

The quotients of the total EC before optimisation divided by the carbon reduction of each strategy are plotted in Figure 8 as EC reduction percentage, with the initial EC percentage for each PC. The x-axis in Figure 8 is the PC indexes, defined in Table 2 for simplicity.

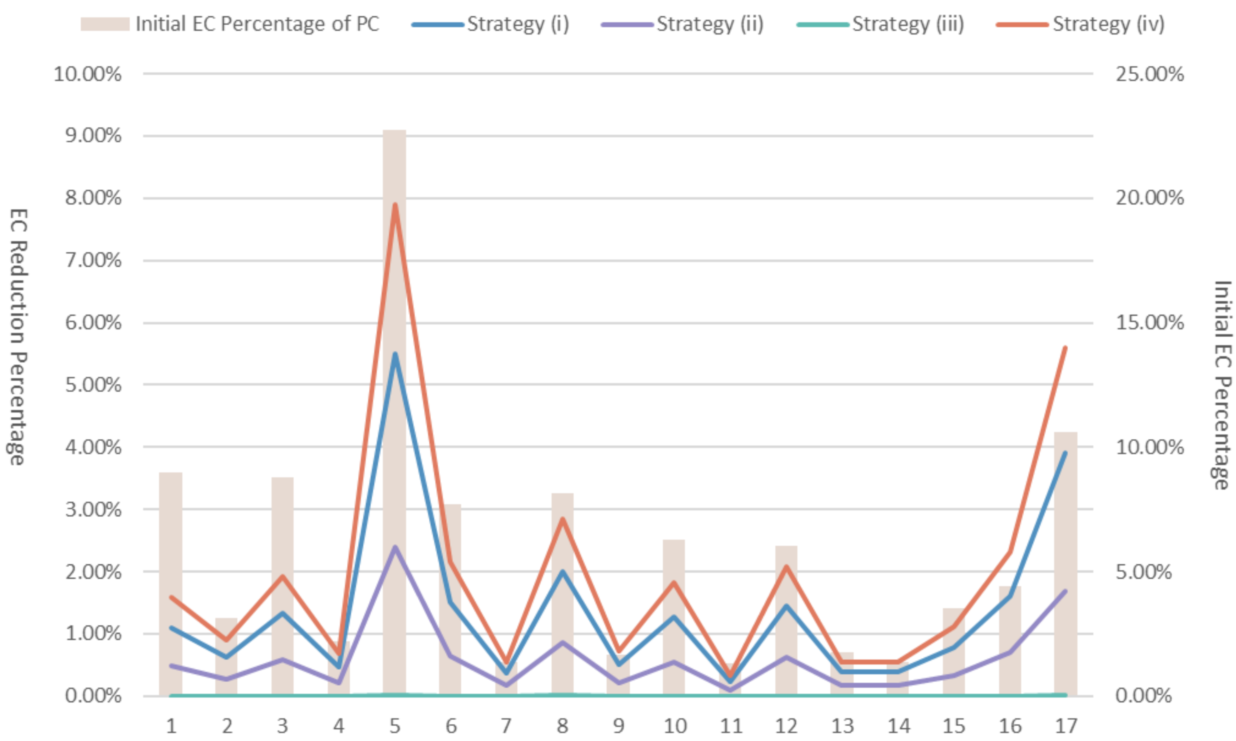


Figure 8. EC reduction percentage for strategies (1) – (4).

The results of EC optimisation can be analysed from two dimensions: replacement strategy dimension and PC dimension. First, the broken line of strategy iv, which combines three independent low-carbon approaches, is always above the other three EC optimisation methods, supporting the perspective of Pomponi and Moncaster (2016) again. Moreover, substituting concrete (i.e., strategy 1) performs better than the other two separate strategies. This implies that the emissions from construction materials represent a significant part of the initial EC, a conclusion echoed by many researchers (Chau et al., 2007; Dong and Ng, 2015; Kofoworola and Gheewala, 2009; Li et al., 2017; Zhang et al., 2013). Therefore, this tool can help designers achieve EC optimisation by providing multiple carbon reduction methods. Second, regarding the EC reduction percentage, the same strategy performs differently on different PCs. If a PC contributes more emissions to the total EC of the project, it can also receive a more significant EC reduction percentage when applying the same strategy. Therefore, the graphical charts can help improve decision-making efficiency concerning EC optimisation by identifying the carbon-intensive PCs.

Table 2. PC name and index.

PC name	PC index
Beam-NS-0-300x600	1
Bean-WE-0-300x600	2
Beam-WE-1-300x600	3
Column-500x500	4
Column-600x600	5
Wall-EW-NS-0	6
Wall-EW-WE-0	7
Wall-EW-WE-1	8
Wall-EW-WE-2	9
Wall-IW-NS-0	10
Wall-IW-NS-1	11
Wall-IW-WE-0	12
Wall-IW-WE-1	13
Wall-IW-WE-2	14
Wall-IW-WE-3	15
Floor-Center	16
Floor-Corner	17

6. Conclusions

This paper presents the successful development of a Revit plug-in for initial EC prediction and optimisation in the design stage. With multiple integrations to enhance the automation level, this plug-in allows users to conduct LCA in Revit without involving other software, which consumes less time and reduces the errors caused by switching between multiple software packages. Unlike most previous studies, which require manual data exchange between BIM and LCA, this plug-in can automatically assign LCA data to each PC. After recognising the adopted materials, the emission factors are automatically attributed to each PC in the production stage. In the construction stage, the quota and related emission factors of auxiliary materials and equipment for on-site assembly are automatically assigned to each PC after identifying each PC's category. The plug-in provides various low-carbon alternatives in the design, transportation, and construction stages. After users select an appropriate option, the BIM model is updated, and the EC is automatically re-calculated. The EC differences before and after the update can be directly shown in Revit.

Nonetheless, some future work is still required to improve the plug-in. First, some real prefabricated building projects will be applied to increase the LCA accuracy. Second, besides EC, other dimensions, such as structural adaptability, can be considered during the carbon optimisation stage. This can be achieved by offering more information when users select the low-carbon substitution strategies, not only the LCA data.

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