A BIM-LCA INTEGRATED METHOD FOR ENHANCING EFFICIENCY OF EMBODIED CARBON ESTIMATION OF PREFABRICATED HIGH-RISE BUILDINGS

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The integration of building information modelling (BIM) and life cycle assessment (LCA) has been increasingly underlined in recent years to simplify the data acquisition in LCA processes. Although BIM can facilitate establishing the bills of quantity (BoQ) for carbon estimation, a great deal of manual work is still needed in current BIM-LCA integrated methods for choosing appropriate LCA databases and assigning corresponding emission factors to construction materials. This research aims to develop an automatic BIM-LCA method to estimate embodied carbon emissions for prefabricated buildings based on a five-level analytical framework, i.e., material, component, assembly, flat, and building. SimaPro was adopted as the LCA platform and three successive modules were conducted, namely, establishment of BIM model, industry foundation classes (IFC)-enabled data transfer between BIM and LCA, and development of BIM-aided LCA model. A case study using a typical floor of a prefabricated high-rise public residential building in Hong Kong was adopted to validate the proposed method. The developed BIM-LCA integrated method achieved automated data extraction from BIM as well as automated data input and update in SimaPro, resulting in an 80% time saving in this case compared with the traditional labour-intensive process. The paper thereby contributes to smart embodied carbon estimation and facilitates quick feedback of embodied carbon emissions during the design phase to support building design efficiency.

Keywords: BIM; embodied carbon emission; LCA; prefabricated building

INTRODUCTION

Climate change has been one of the most urgent environmental issues facing mankind. As the primary driver of climate change, carbon emissions have increased rapidly in recent years. Among all the carbon emitters, the architecture, engineering, and construction (AEC) sector plays an important role (Sadineni *et al.,* 2011). In high-rise high-density cities like Hong Kong, buildings account for over 60% of carbon emissions (ENVB 2017). Apart from the operational carbon, the embodied carbon emissions generated from the production, transportation, construction, replacement, and end-of-life of building components are also responsible for a large share of total carbon emissions with the emerging trend of using low/zero carbon design (Teng and Pan 2019). The manufacturing of building materials alone represents 5~10% of the global carbon emissions. It is thus important to address the embodied carbon estimation and reduction of buildings during the design stage. However, life cycle

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Xu, J, Teng, Y and Pan, W (2021) A BIM-LCA Integrated Method for Enhancing Efficiency of Embodied Carbon Estimation of Prefabricated High-Rise Buildings *In:* Scott, L and Neilson, C J (Eds) *Proceedings of the 37th Annual ARCOM Conference,* 6-7 September 2021, UK, Association of Researchers in Construction Management, 14-23

assessment (LCA) of buildings is a complex, time-consuming, and labour-intensive task since a large amount of information is required and selecting a representative dataset for a non-professional personage is difficult. As a result, the LCA of buildings is commonly conducted at the end of the design stage, when necessary, information is available, which is often too late to guide the design decision-making.

Building Information Modelling (BIM) can facilitate establishing the bills of quantity (BoQ) and support project teams by providing immediate insight into how design decisions affect the building performance. Hence, BIM is increasingly used to explore design solutions to improve the life cycle performance (Eleftheriadis *et al.,* 2017). BIM-LCA integration is a powerful approach to perform LCA for buildings during the design process and a growing number of applications is underlined in recent papers. For example, the most widely adopted method is to extract material quantities from BIM and carbon emission factors from LCA databases, and then to conduct the calculation in Excel (Peng *et al.,* 2016; Feng *et al.,* 2020). However, a great deal of manual work is still needed for choosing appropriate LCA databases and assigning corresponding emission factors to construction materials. Data interoperability between BIM models and LCA databases is another main challenge of current BIM-LCA integration. Different data formats of the material databases in BIM and LCA tools such as units, types, and names hinder the data mapping process (Yang *et al.,* 2018). Moreover, material databases in BIM software tools are usually not as detailed as LCA databases such as Ecoinvent so that materials obtained from BIM models may have several options of the impact factors (Rezaei *et al.,* 2019). All these limitations impair the efficiency and convenience of BIM-LCA methods.

The aim of this paper is to develop a BIM-LCA integrated method for enhancing the efficiency of embodied carbon estimation of prefabricated high-rise buildings. SimaPro was selected for conducting the LCA process as it is one of the leading software tools used for life cycle assessment and has been used in more than 80 countries. It has integrated with several LCA databases like Ecoinvent, ETH-ESU 96, U.S. LCI, EF, and so on, which can provide sufficient carbon emission factors of materials and energy. It can offer accurate and reliable carbon results, which was demonstrated by the comparison with other LCA tools such as GaBi and OpenLCA (Herrmann and Moltesen 2015). Interoperability between BIM and LCA was addressed by developing an Industry Foundation Classes (IFC)-enabled data transfer tool to transmit necessary data from BIM to SimaPro. This paper can achieve automated data extraction from BIM and automated data input in SimaPro, which gains a significant efficiency promotion in embodied carbon estimation compared with the traditional labour-intensive process. Moreover, the automatic updating of the LCA model in SimaPro can be conducted with any design alteration in the BIM model, so as to better facilitate quick feedback of embodied carbon emissions during the design phase to support building design efficiency.

Previous Studies On BIM-LCA Integration

To simplify and reduce the data acquisition during LCA application in building design, lots of researchers have developed innovative BIM-LCA integration methods in recent years. Antón and Díaz (2014) proposed two approaches for the integration of BIM and LCA. The first approach was to use automatic take-off tools to extract information directly from the BIM model, which were then combined with life cycle inventory data to perform an accurate LCA. The second approach was to incorporate environmental information into BIM objects to support decision-making. Wastiels and Decuypere (2019) reviewed relevant papers and concluded five BIM-LCA integrated strategies, namely importing a BIM-based BoQ report into dedicated LCA software, importing BIM model into dedicated LCA software through IFC format, using a BIM viewer tool to associate LCA data to building components, using an LCA plug-in of BIM software, and establishing BIM objects with enriched LCA information or references. Taking different calculation platforms as the critical factor, previous BIM-LCA integration can be classified into four categories. A comprehensive description of representative cases for each category is listed in Table 1.

Table 1: Representative cases for BIM-LCA integration

Year	Authors	Adopted tools/methods	Category
2016	Peng	Revit; Literature; Excel	Type I
2016	Shadram *et al.*	Revit; EPD; PowerPivot	Type II
2017	Abanda *et al.*	Revit; Navisworks; Bath ICE Database; Revit API	Type III
2018	Yang *et al.*	Revit; Glondon; Chinese Life Cycle Database; Ecoinvent; eBalance	Type IV
2019	Cavalliere *et al.*	Rhinoceros; Swiss Buildings Database; Bauteilkatalog; KBOB; Excel	Type I
2019	Rezaei *et al.*	Revit; Ecoinvent; openLCA	Type IV
2020	Ding *et al.*	Revit; literature/report/handbook; Access	Type II
2020	Feng *et al.*	Revit; Ecoinvent; Excel	Type I
2020	Kiamili *et al.*	Revit; KBOB; Ecoinvent; Dynamo	Type III
2020	Santos *et al.*	Revit; EPD; generic database; BIMEELCA	Type III

The first type (Type I) is to use Excel as the calculation tool of carbon emissions, which is the most widely adopted method due to its simplicity and quick feedback irrespective of dedicated software tools. Material quantities are obtained and exported into Excel spreadsheets through element functions in various BIM tools such as Revit, ArchiCAD, and Rhinoceros. Emission factors are acquired from various LCA data sources. The second type (Type II) holds the same mechanism as Type I to acquire engineering quantities and emission factors while author-developed applications using Access, SQL language, C# net, and python instead of Excel are adopted to streamline the calculation process. The third type (Type III) performs a simplified LCA in the native BIM environment with LCA data inserted into objects or an embedded database. In this case, Revit is the most commonly used BIM software tool due to its accessibility to application programming interface (API) development. Such methods make full use of BIM technology in terms of flexible data modification, integrated data storage, quick feedback, and intuitive visualization. The fourth type (Type IV) is superior in the professionalism and reliability by importing the BIM data into dedicated LCA software tools for an accurate and comprehensive LCA. Material quantities generated from BIM can help to facilitate the establishment of LCA models.

Despite numerous advantages mentioned in BIM-LCA integrated methods, two challenges have been discovered and emphasized. The burdensome and cumbersome process of selecting proper LCA data from diverse data sources has been regarded as the first challenge. Generally, researchers obtain LCA data from LCA databases, environmental product declaration (EPD), or literature/report. It is usually time-consuming to collect all the carbon emission factors for materials and energy because one generic database cannot provide sufficient data especially in different regional contexts and accordingly a transversal search in several data sources is imperative. Data interoperability between BIM and LCA tools remains as the other challenge. An intermediate tool is required for data exchange to accommodate the data to a common structure. It is thus recommended that the development of data exchange tools based on open data format such as IFC is superior to the development of specific plug-ins of certain BIM software.

Therefore, this paper adopts the fourth type of BIM-LCA integration by using SimaPro as the calculation platform, eliminating the manual work of selecting and collecting LCA data and better facilitating sensitivity analysis to perform an accurate and comprehensive LCA. To overcome the limitation of data interoperability between BIM and SimaPro, an automated data mapping and transferring approach based on IFC schema was developed for embodied carbon estimation of prefabricated buildings.

METHODOLOGY

This section presents the methodology for the development of the proposed automatic BIM-LCA integrated method to estimate embodied carbon emissions for prefabricated buildings (Fig 1). The study was implemented through four steps: 1) establishment of BIM model, 2) data transfer between BIM and LCA, 3) development of BIM-aided LCA model, and 4) model efficiency validation. The whole process was based on a five-level analytical framework developed by Pan *et al.* (2018), i.e. material (e.g. concrete, steel), component (e.g. precast slab, precast staircase), assembly (e.g. non-volumetric precast facade and volumetric precast kitchen unit), flat (a residential unit), and building (the entire building), for estimating prefabricated buildings' life cycle carbon emissions.

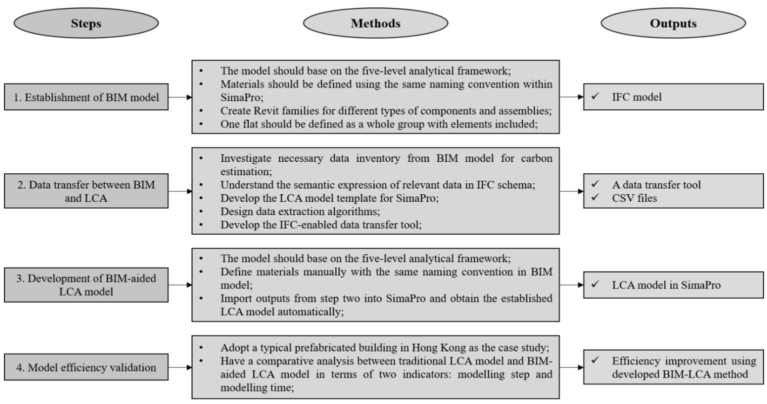


Fig 1: Methodology framework for the development of the proposed BIM-LCA method

Establishment of BIM model

According to the five-level framework, embodied carbon emissions for prefabricated buildings were estimated at the levels of material, component, assembly, flat, and building. To automatically and accurately provide the containment relationship among five levels, the BIM model was established based on the five-level framework. At the material level, a naming convention was determined for both the BIM model and LCA model to tackle the data mapping issue. For components and assemblies of prefabricated buildings, the resources provided by the embedded component library of BIM software were inadequate so that new family types were created according to building information. Then all relevant components and assemblies were assigned into a whole group to identify various units at the flat level.

Data transfer between BIM and LCA

An IFC-enabled data transfer method was adopted to extract necessary data from the BIM model and to convert data into an appropriate format of SimaPro. IFC is a common data standard supported by numerous BIM software tools. Instead of developing specific plug-ins using APIs for specific BIM software tools, IFC-enabled data processing is more general without software limitation. Moreover, it is possible to define the containment relationship among five levels using sub-instances of IfcRelationship in IFC schema, which cannot be explicitly expressed in BIM software. Fig 2 demonstrates the data flow of the IFC-enabled data transfer method. The data transfer tool was developed using python after investigating the data inventory for carbon estimation and exploiting data extraction algorithms based on IFC schema. The proposed method achieves automated data conversion from BIM to SimaPro, reducing huge manual work and enhancing data interoperability between BIM and LCA.

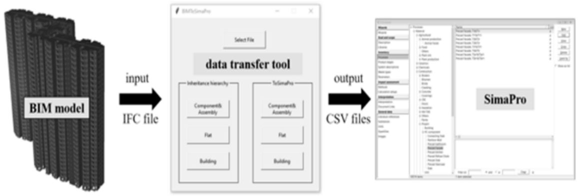


Fig 2: Data flow of the IFC-enabled data transfer method

Development of BIM-aided LCA model

Building elements are defined as products in the LCA model in SimaPro, which consist of corresponding carbon emitters. For traditional buildings without consideration of prefabricated systems, only three-level products need to be created namely material, individual component, and entire building. However, five-level products were established to obtain embodied carbon emissions for prefabricated buildings at the levels of material, component, assembly, flat, and building. The compositions of products were assigned based on the containment relationship among five levels. Fig 3 illustrates the overall framework of the BIM-aided LCA modelling process.

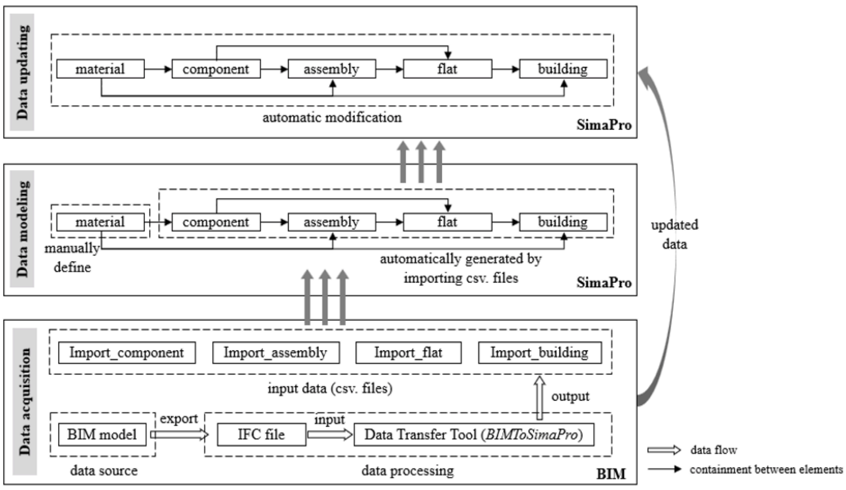


Fig 3: Framework of the BIM-aided LCA modelling method in SimaPro

For data acquisition, material quantities and containment relationships among elements could be directly obtained from the BIM model instead of asking project teams for site documents and building drawings or interviewing with stakeholders (Teng and Pan 2020) in the traditional case. Products at the material level included detailed material ingredients, consumed fuels, and transportation data during the material production process, which exceeded the usual level of detail (LOD) of the

BIM model. As a result, manual data input at the material level was inevitable and materials should conform to the naming convention in the design model to guarantee the automated mapping processes. Products at the other four levels of component, assembly, flat, and building were automatically set up by importing SimaPro-accessible files generated from the data transfer tool. Furthermore, automated updating of the LCA model in accordance with the design modification in BIM was realized by reimporting update files and overriding original data. The development of the BIM-aided LCA model eliminates large amounts of human efforts through an intelligent, rapid, and simultaneous establishment of numerous products rather than a separate and successive modelling. It also facilitates quick feedback of embodied carbon emissions for different design options during the design phase.

Model efficiency validation

The empirical validation of the LCA model was then implemented through a real case study. A typical floor of a 30-storey prefabricated residential building in Hong Kong was selected as it conforms to the five-level prefabricated system and it is able to validate the efficiency promotion through comparison with previous study using the same case, which was conducted by Teng and Pan (2019) for assessing embodied carbon emissions using the traditional LCA method. After adopting the proposed BIM-LCA method, the model efficiency validation was carried out by comparing LCA modelling steps and modelling time between BIM-aided method and traditional method. Fig 4 shows the BIM model and layout of the typical floor, including diverse types of prefabricated components and assemblies.

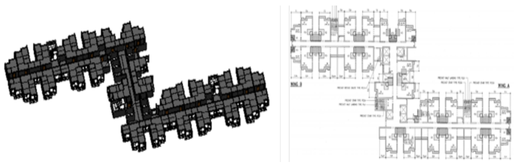


Fig 4: BIM model and layout of the typical floor in case building

Based on the five-level analytical framework, the containment relationships among elements of the typical floor are demonstrated in Table 2. The number of types for each product is included in the parenthesis. The typical floor involves flats and individual components such as precast staircases, precast refuse chute, and connecting slabs. Each flat may contain several assemblies and components like precast kitchen, precast bathroom, precast façade, partition walls, and precast slabs. For prefabricated products, the parameters of concrete amount and steel weight were extracted individually, while only a total amount was calculated for cast-in-situ materials at the building level. A comparative analysis between the traditional modelling method and the BIM-aided modelling method in SimaPro was conducted for assessing the efficiency improvement of the proposed BIM-LCA integrated method.

RESULTS AND ANALYSIS

Two types of indicators were selected for evaluating the model efficiency, namely modelling step, and modelling time. The material ingredients were not defined in the BIM model and the products at the material level still remained manual input. The model efficiency promotion is therefore evaluated at the component, assembly, flat and building levels.

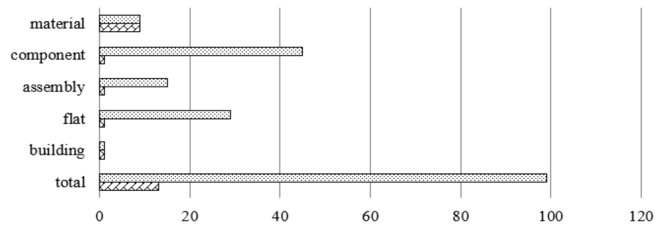
Fig 5 shows the comparative result of modelling steps at five levels of material, component, assembly, flat, and building for the case floor. In the traditional method, modelling steps depend on product types. For example, only one product at the building level was established in this study as only one typical floor was selected. If considering the whole building, thirty steps would be needed to establish thirty products at the building level. However, in the proposed BIM-aided method, modelling steps at four levels apart from material level are independent of case specification owing to the data import function provided by SimaPro.

Table 2: Elements in the five-level LCA model of the case

Level	Product	Composition
Building	floor (1)	unit, connecting slab, precast refuse chute, precast staircase, on-site concrete, on-site steel
Flat	unit (29)	precast façade, precast bathroom, precast kitchen, partition wall, precast slab
Assembly	precast façade (8); precast kitchen (3); precast bathroom (3); precast refuse chute (1)	concrete; steel
Component	partition wall (2); precast staircase (4); connecting slab (25); precast slab (14)	concrete; steel
Material	concrete (8); steel (1)	material ingredients; consumed fuels; transportation

Note: The number in parenthesis represents the number of types for each product.

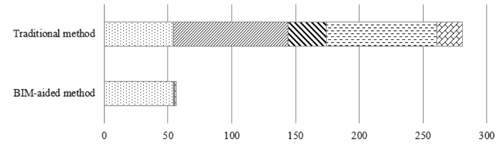
The LCA model was automatically established through importing CSV files generated by the developed data transfer tool, which involves necessary information of products and corresponding compositions. Therefore, only the step of importing data was needed at these four levels. Fig 5 indicated that a total number of 86 modelling steps were omitted in this case, reducing repeated manual work and simplifying the establishing process of LCA model. At the levels of component, assembly, flat, and building, more types of products lead to more traditional modelling steps, resulting in higher step reduction. Thus, if applying the BIM-LCA method to the whole case building, more steps could be reduced during the LCA modelling process compared with the traditional method.



	material	component	assembly	flat	building	total
Traditional method	9	45	15	29	1	99
BIM-aided method	9	1	1	1	1	13
step reduction	0	44	14	28	0	86

Fig 5: Comparative result of modelling steps for the case study

Fig 6 illustrates the comparative results of modelling time and efficiency improvement of the case building at the five levels. In the traditional LCA method, time estimation was based on mean value since the processes of and time spent on creating products at each level were similar. Ten products at each level were randomly selected as samples for calculating the average modelling time. In this case, it took an average of 6, 2, 2, 3, and 20 minutes to establish one product at the levels of material, component, assembly, flat, and building, respectively. Thus, the total modelling time could be estimated by multiplying the mean value by the number of product types. When importing files in the BIM-aided method, it all took around thirty seconds for data input at each level regardless of the file size and element quantities. It implies a high-performance potential of data processing in LCA model establishment. The right part of Fig 6 provides the time efficiency improvement at five levels. A significant enhancement of time efficiency above 97% was achieved in terms of component, assembly, flat, and building, while the total improvement decreased to 80% considering the whole process. It indicates that the process of creating materials plays a vital role in LCA model establishment so that it is important to promote smart data input at the material level in further research.



	material	component	assembly	flat	building	total
Traditional method	54	90	30	87	20	281
BIM-aided method	54	0.5	0.5	0.5	0.5	56

Note: time is measured in minutes

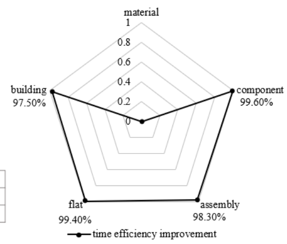


Fig 6: Comparative result of modelling time for the case study

DISCUSSION

The proposed BIM-LCA integrated method aims to enhance the efficiency of embodied carbon estimation for prefabricated high-rise buildings based on a five-level analytical framework. Compared with previous BIM-LCA research, two kinds of research gaps were effectively addressed. First, by adopting SimaPro as the calculation platform, human efforts are reduced in seeking various LCA data sources such as databases, EPD, and literature (Ding *et al.,* 2020; Santos *et al.,* 2020) as well as extracting data into excel templates (Feng *et al.,* 2020). Additionally, dedicated LCA software can better facilitate scenario analysis and uncertainty analysis for embodied carbon emissions whereas only simple multiplication was conducted in most traditional BIM-LCA integration. Second, an IFC-enabled data transfer tool was developed to automatically adapt the BIM data to SimaPro-accessible LCA data structure. By investigating the data inventory for carbon estimation and semantic expression of relevant data in the IFC schema, data processing algorithms were developed for the tool. Besides, a naming convention was established for data mapping of materials. The developed tool can achieve automated data transfer from BIM to SimaPro, greatly enhancing the data interoperability between BIM and LCA. Third, the result of the case study using a typical floor of a prefabricated residential building validated the model efficiency of the proposed method. A total of 86 modelling steps were reduced and an 80 percent efficiency improvement in modelling time was realized. The reduction of modelling steps and modelling time makes the establishment of LCA model in SimaPro a more simplified and convenient process, decreasing the difficulty of using dedicated LCA tools and motivating more accurate and comprehensive LCA applications. However, the result is more of a qualitative analysis of efficiency promotion rather than a quantitative analysis because it depends on many parameters. At the case level, it is relevant to case specifications such as building height, floor areas, product types at five levels, compositions of products, etc. At the operation level, personal proficiency of BIM software and SimaPro, personal familiarity of the case building, and operation habits can also influence the testing result. Nevertheless, it can be concluded that the proposed BIM-LCA method can indeed enhance the efficiency of embodied carbon estimation of prefabricated high-rise buildings through automated data manipulation.

CONCLUSIONS

To reduce human efforts in LCA data extraction and data mapping between BIM and LCA in previous research, this paper develops an automatic BIM-LCA integrated method to estimate embodied carbon emissions for prefabricated buildings based on a five-level analytical framework, i.e., material, component, assembly, flat, and building. The method includes three successive modules. First, a few criteria should be made for the establishment of the BIM model to define containment relationships of elements in the context of prefabricated buildings. Second, automatic data conversion can be achieved using the developed IFC-enabled data transfer tool. Finally, the LCA model in SimaPro can be automatically established by importing generated files from the second module. The method adopts the five-level analytical framework for embodied carbon estimation, promoting the standardization and benchmarking of prefabricated buildings' embodied carbon. Nevertheless, there are two limitations of this proposed method. First, it was developed based on the five-level analytical framework adapted from the prefabrication system in Hong Kong and it is thus only applicable to similar prefabricated systems comprising such five levels. However, the approach to defining the containment relationships among products at different levels in the LCA model can be applied in other prefabrication systems worldwide. Second, the method is limited to specific LCA software-SimaPro since the data transfer tool was developed according to the LCA data structure in SimaPro. However, it provides an innovative idea to enhance the data interoperability between BIM and LCA by adapting the data into a common data structure and new data processing algorithms should be exploited when considering other LCA tools. Overall, this innovative BIM-LCA method achieved a significant improvement to embodied carbon estimation efficiency compared with the traditional labour-intensive process through a real case empirical validation, contributing to a smart and convenient embodied carbon estimation and facilitating quick feedback of embodied carbon emissions to support building design efficiency. A comprehensive LCA study requires more kinds of data such as formwork, electricity, transportation, etc., which however are not considered in this method. Therefore, integrating more data into the LCA model using BIM or other smart technologies is recommended for future research.

ACKNOWLEDGMENTS

This work was supported by a grant from the General Research Fund of the Hong Kong Research Grants Council [Project No.: 17203219].

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