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A critical review on BIM and LCA integration using the ISO 14040 framework

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ABSTRACT

The application of building information modelling (BIM) in life cycle assessment (LCA) brings significant benefits, resulting in increasing publications in the field of BIM-LCA integration. However, there is no systematic examination on the present status in BIM-LCA integration. In this regard, ISO 14040 standard series provides a systematic framework. This study investigates the latest research development in BIM-LCA integration using ISO 14040 framework. The analysis focused on research studies on data collection, data mapping and data exchange between BIM and LCA data and expression of buildings' environmental impacts from 2012 to 2021. 61 articles have been collected and analysed by using content analysis methods. The results indicate that LCA data sources are well presented in BIM-LCA integration studies but the accessibility of data from BIM model is poor. Moreover, manual work is the most popular method for data exchange. Environmental impacts from buildings are mainly presented in traditional ways such as bar charts and pie charts. This study also reveals that majority of BIM-LCA integration studies focus on comparing design alternatives. Findings of this research study identified several unaddressed issues, such as lack of understanding in applicability of each BIM-LCA integration approach and unified structure between BIM and LCA data. By drawing on these findings, authors provide recommendations on improving BIM-LCA integration, such as recommending to create strategies for selecting suitable integration approaches for different LCA scenarios. This research provides academics and practitioners with a comprehensive understanding in the current development of BIM-LCA integration, and heuristic implications for future studies.

1. Introduction

Life cycle assessment (LCA) is a powerful tool for quantifying environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave) [1]. This tool is often adopted to building sector for optimizing a building's design by analysing its potential of reducing resource consumption and environmental pollution [2,3]. Nevertheless, LCA application in buildings faces numerous challenges, such as the difficulties in collecting information of life cycle inventory, the complexities of conducting impact assessment, the difficulties in interpreting LCA results, and the consumption on time and labour [4–6]. Building information modelling (BIM) digitally represents the physical and functional characteristics of a facility and related information of the building project [7]. BIM application in buildings' environmental impact assessment provides valuable information about life cycle inventory across a building's life cycle, such as material specifications, quantity take-offs, and other information about building components and materials [8,9]. By integrating BIM models with LCA tools, the relevant data can automatically be retrieved and input, and therefore both time and labour can be saved [10,11]. Furthermore, the combination of BIM and LCA tools enables to generate quick evaluation results of all possible design solutions and thus provides supports for decision making at the design stages [3,12,13].

Given these benefits, a growing number of studies concerning BIM and LCA have occurred to encourage BIM application in buildings' environmental impact assessment over the past decade. Although this development has enriched the knowledge in this discipline, only after 2013 publications concerning BIM and LCA integration have been growing dramatically [14]. Consequently, it brings difficulties for researchers to have a full and comprehensive understanding on the

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research progress and achievements in BIM-LCA integration in a short time. As a result, the great potentials of applying collectively BIM and LCA tools fail to be fully exploited [15]. Therefore, it is considered important to systematically examine the research efforts on BIM-LCA integration to provide sufficient understandings on the latest development of this discipline and to help promote the application of BIM in LCA implementation.

Several literature reviews associated with BIM and LCA integration have been published over the past few years. Mainstream review articles focused on exploring the benefits and challenges of combining BIM and LCA tools to assess the environmental impacts of buildings [16–18]. Several approaches have been developed to overcome the challenges facing BIM and LCA integration and to facilitate the application of BIM in LCA implementation. These integration approaches have been reviewed and classified in line with different principles. For example, Soust-Verdaguer et al. [9] investigated BIM-LCA integration approaches proposed in previous case studies from the perspective of data input, data analysis, and data output. These BIM-LCA integration approaches are grouped into two types: 1) BIM plugins for LCA, and 2) combining different data and software for automated LCA processes. In another study by Obrecht et al. [19], according to the automation degree, BIM-LCA integration approaches are classified into three types: 1) manual, 2) semi-automated, and 3) full-automated. However, these studies focus on classifying BIM-LCA integration approaches yet there is a lack of research on analysing the interactive processes between BIM and LCA tools during LCA implementation. As a result, interoperability-related issues in BIM and LCA integration remain unaddressed. A couple of other review articles attempted to investigate the parameters involved in BIM-LCA integration processes. For example, Mora et al. [20] suggested the key parameters for BIM-LCA integration including LCA and BIM tools, functional unit, and LCA databases. Similarly, the applicability of existing LCA databases for the new assessment circumstances implicated by BIM- LCA integration has been analysed [21]. The research results highlighted the strength of existing LCA databases. In another study, Hollberg et al. [22] reviewed the ways to present LCA results and suggested that the use of colour code in BIM models for visualization of LCA results needs to be enhanced.

Above discussion reveals that despite the growing understanding of required information in BIM and LCA integration, research associated with the interactive processes between BIM and LCA tools remains scarce. There is still no systematic review on the current developments in BIM-LCA integration that shows the interactivity between BIM and LCA tools during LCA implementation. The novelty of this work is to conduct a systematic review on the interactive processes between BIM and LCA tools in BIM-LCA integration studies over the past decade by using a standardised and general framework.

In this regard, there are several globally recognized frameworks for LCA implementation. For example, ISO 14040 standard series (i.e., ISO 14040 and ISO 14044), first published by the International Organization for Standardization (ISO) in 1997, have harmonized these methods and procedures for LCA implementation and created a general methodological framework. This standard series was revised and published in 2006 to provide principles and a framework to support LCA implementation. In addition to the ISO 14040 standards, there are standards specifically targeting building sector, such as ISO 21930, EN 15978, EN15942, and others [23–25]. However, these standards are developed based on data obtained from Environmental Product Declarations (EPDs) for construction products, and do not directly present a framework of LCA implementation. Very few BIM-LCA integration studies have been executed according to these standards. On this point, although ISO 14040 standard series provides a general systematic framework for conducting an LCA, the application of the ISO 14040 framework has been well received in previous BIM-LCA integration studies [12,26,27]. Therefore, it is imperative to have a systematic insight into the integration processes between BIM and LCA by referring to the framework of ISO 14040 standards. In view of this background, this article explores the existing state-of-the-art research efforts related to BIM-LCA integration using ISO 14040 standards. By drawing on the review findings, unaddressed issues in BIM-LCA integration are identified, and corresponding future perspectives are proposed.

2. Research design

This research aims to provide a systematic review on the interactive processes between BIM and LCA tools in BIM-LCA integration studies by using ISO 14040 standards. To achieve the defined research objective, this research is designed as follows: 1) to identify the key phases of BIM-LCA integration under the framework of ISO 14040 and to define the criteria in each key phase for analysing the present research efforts on BIM-LCA integration, 2) to examine the present status of BIM-LCA integration against each criterion in each key phase by employing content analysis, 3) to identify the unaddressed issues in BIM-LCA integration based on the content analysis results, and 4) to perceive the future perspectives in terms of how the integration between BIM and LCA can be improved in line with the identified issues. Fig. 1 illustrates the framework for the research design.

2.1. Key phases and criteria for analysing BIM-LCA integration using ISO 14040 framework

ISO 14040 framework provides a standard process for LCA implementation. There are four required phases in conducting LCA using this framework, including 1) goal and scope definition, 2) life cycle inventory analysis (LCI), 3) life cycle impact assessment (LCIA), and 4) life cycle interpretation [1,28]. The relationships among the four phases are shown in Fig. 2. In goal and scope definition phase, the assumption, the system boundary, and the purpose and objectives of the study are stated. The LCI phase involves collection of data necessary to meet the goals of the defined study. In LCIA phase, the purpose is to provide additional information to help assess a product system's LCI results so as to better understand their environmental significance. In life cycle interpretation phase, the results of LCI and LCIA are summarized and discussed as a basis for recommendations and decision-making in accordance with the goal and scope definition.

Although ISO 14040 framework does not specifically target building sector, most BIM-LCA integration studies have used this framework to conduct LCA because it is widely used, and it is a harmonized version and provides a general methodological framework that can be well adopted for buildings. Therefore, the current status of BIM-LCA integrated processes is analysed by referring to the framework of ISO 14040 standard. The procedures for performing a BIM-based LCA are the same as those for conducting an LCA using the ISO 14040 framework [1,12,28]. Fig. 2 illustrates interactive processes between BIM and LCA tools in each phase of ISO 14040 framework and the criteria used in this research to examine the present status of BIM-LCA integration. In goal and scope definition phase, background information of buildings (e.g., buildings' life span) can be defined in BIM models, and assumptions (e.g., about the disposal of wastes) can be made to assist with buildings' environmental impact evaluation. However, BIM-LCA integration appears not at the goal and scope definition phase, but at the LCI, LCIA, and interpretation phases [12], as shown in Fig. 2. Each of these phases is further explained in the flowing parts of this subsection.

2.1.1. BIM-LCA integration at LCI phase

In LCI phase, BIM-LCA integration refers to extracting information on building material from BIM models and allocating it to the available LCA data for LCI results [29]. There are three steps in this process: 1) data collection from BIM model and LCA data, 2) data mapping between data from BIM model and LCA data, and 3) data exchange between BIM and LCA tools in various BIM-LCA integration approaches used for calculating LCI results.

In data collection, data from the BIM model and LCA data are

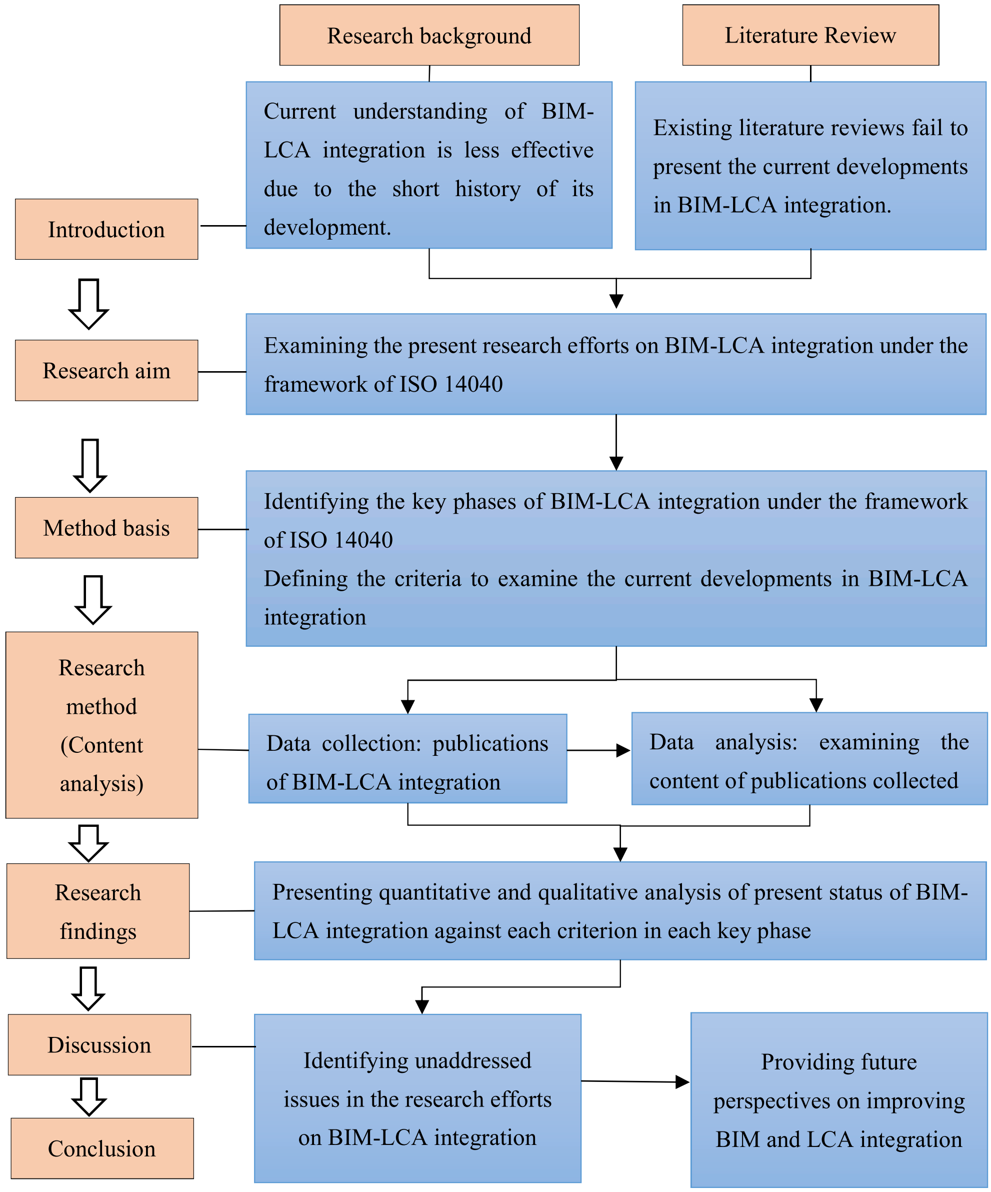


Fig. 1. Research framework of the research design.

collected from different sources. Data regarding building geometry and physical characteristics can be directly extracted from BIM models. The accessibility of BIM model's data can be indicated by the level of details (LOD) of a BIM model as LOD defines the richness of the graphic and data information of a BIM model [30]. There are five progressively detailed levels from LOD 100 to LOD 500 and a more detailed level of a BIM model implies more building information contained in the BIM model. On the other hand, LCA data can be retrieved from existing or adapted LCA databases. There are four sources for collecting existing LCA data: 1) literature or standards, 2) in-house databases in LCA tools, 3) international or national LCA databases, and 4) environmental product declaration (EPD) [31]. Therefore, the performance in data collection can be examined by checking the adopted LODs and the LCA data source in BIM-LCA integration studies.

Data from BIM model and LCA data vary in data format. When a link between BIM data and LCA data is to be set, a unified data structure and common naming convention for both kinds of data should be established in order to provide a transparent process for mapping data from BIM model into LCA data [19]. Since the data structure and naming convention in LCA databases are fixed and hard to disaggregate, the data structure and naming convention of data from BIM models are often modified for mapping into LCA data during the data mapping process. Therefore, the performance in data mapping between the data from BIM model and LCA data can be examined by checking the adopted data structure and naming conventions used in data from BIM model in BIM-LCA integration studies.

Data from the BIM model is transferred into LCA tools for calculating LCI results during the 'data exchange' process. There are six types to exchange data from the BIM model and LCA data: Type 1) exporting bill of quantities (BOQ) into Excel, Type 2) exporting BOQ into dedicated LCA tool, Type 3) adopting LCA plugin for BIM-software, Type 4) using industry foundation classes (IFC) format of BIM models for data transfer, Type 5) using visual programming languages (VPL) for environmental impact evaluation, and Type 6) including LCA information in BIM objects [19,32]. Data transfer from BIM models to LCA tools is carried out manually when using the method of type 1 or type 2 [33]. Although manual work can be avoided by using other data exchange methods, their preparation work is much more complex than the manual methods [34]. Therefore, the performance in data exchange between BIM and LCA tools can be examined by checking the methods of data exchange

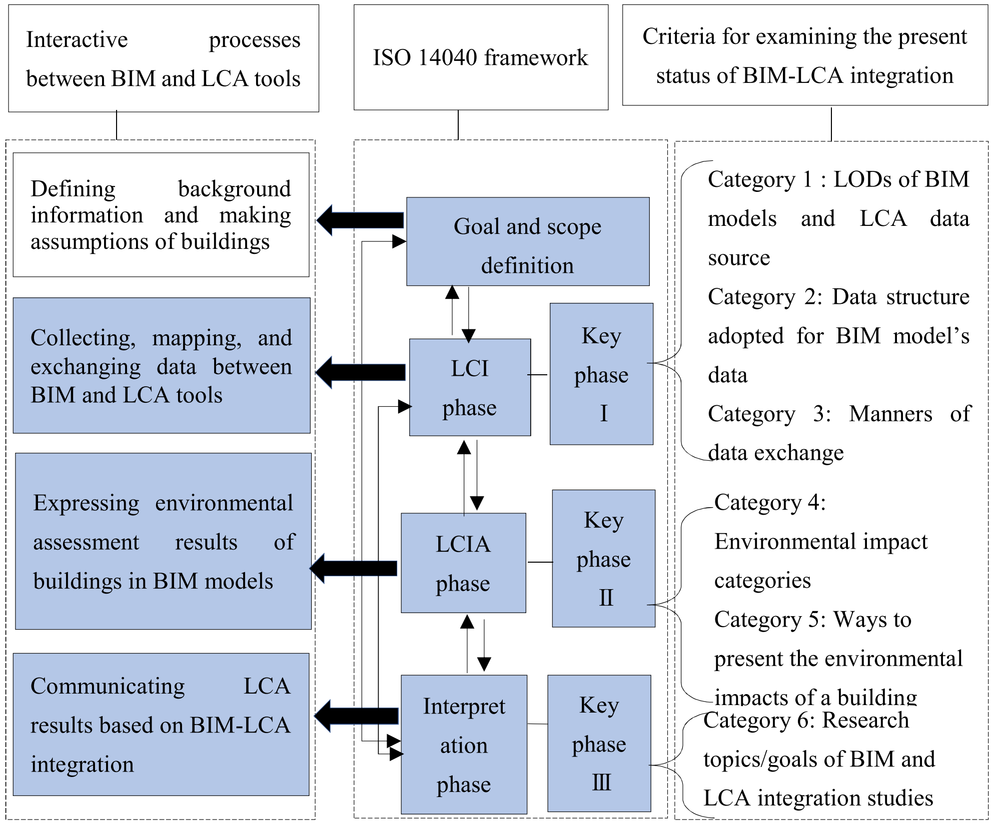


Fig. 2. Key phases and criteria for examining BIM-LCA integration.

adopted in BIM-LCA integration studies.

In view of above analysis, LCI phase can be considered as a key phase for BIM-LCA integration under the framework of ISO 14040. The criteria for examining the performance of BIM-LCA integration at LCI phase are: 1) LODs of BIM models and LCA data source, 2) data structure and naming convention adopted for the data from BIM model, 3) manners of data exchange between BIM and LCA tools (refer Fig. 2).

2.1.2. *BIM-LCA integration at LCIA phase*

In LCIA phase, the principle is to understand and evaluate the magnitude and significance of the potential environmental impacts of a building throughout the life cycle [1]. There are two steps in this process: 1) identify the indicators used to provide LCI results, 2) identify the way in which the LCI results to be presented because environmental impacts from a building can be presented through different visualization ways, such as bar chart, BIM models and others [35]. There are several indicators used to provide LCI results in step 1. For example, the environmental impact from carbon emissions can be given using an indicator such as the global warming potential (GWP). Therefore, the adopted environmental impact indicators and ways to present environmental impacts can be used to indicate the performance of BIM-LCA integration in LCIA phase. The criteria for examining the current status of BIM-LCA integration in LCIA phase are: 1) environmental impact indicators, and 2) ways to present the environmental impacts of a building (refer Fig. 2).

2.1.3. *BIM-LCA integration at interpretation phase*

In interpretation phase, the results from LCI and/or LCIA phases are further analysed in line with the defined goals to reach conclusion, explain limitations, and provide suggestions [1]. The goals defined in BIM-LCA integration vary between studies to a large extent. For example, some studies adopt BIM-LCA integration approaches for identifying the hotspots of environmental impacts of a building [32,36], while some other studies attempt to compare the design or construction alternatives [10,37]. There are various research goals on studies related to BIM-LCA integration. The performance of BIM-LCA integration in interpretation phase can be examined by checking the research goals or typical research topics in BIM-LCA integration research studies.

To sum up, LCI, LCIA, and interpretation phases of in ISO 14040 framework are identified as the key phases for BIM-LCA integration. Six criteria for examining the present status of BIM-LCA integration in the three key phases are defined as 1) LODs of BIM model and LCA data source (criteria for LCI phase), 2) data structure and naming convention adopted for data from the BIM model (criteria for LCI phase), 3) manners of data exchange (criteria for LCI phase), 4) environmental impact indicators (criteria for LCIA phase), 5) ways to present the environmental impacts of a building (criteria for LCIA phase), and 6) research topics and/or research goals in BIM-LCA integration studies (criteria for interpretation phase) (refer Fig. 2).

2.2. *Research method*

This research adopts content analysis method for examining research studies on BIM-LCA integration from 2012 to 2021 (over the past decade). Content analysis is a text data analysis technique that explicitly elaborates the content of the collected literature based on the defined categories [38]. There are two reasons for adopting this method in this study. First, content analysis focus on the intentions, content, and consequences of collected literature, which allows for dealing with both manifest and latent content and supports a comprehensive understanding of the research efforts on BIM-LCA integration [39]. Furthermore, the effectiveness of applying content analysis in building and construction fields has been evidenced in previous studies [40,41]. In line with the principles of this method [38], the implementation of content analysis consists of two steps: data collection and data analysis. Fig. 3 illustrates the detailed procedures of conducting content analysis to examine the existing literature on BIM-LCA integration.

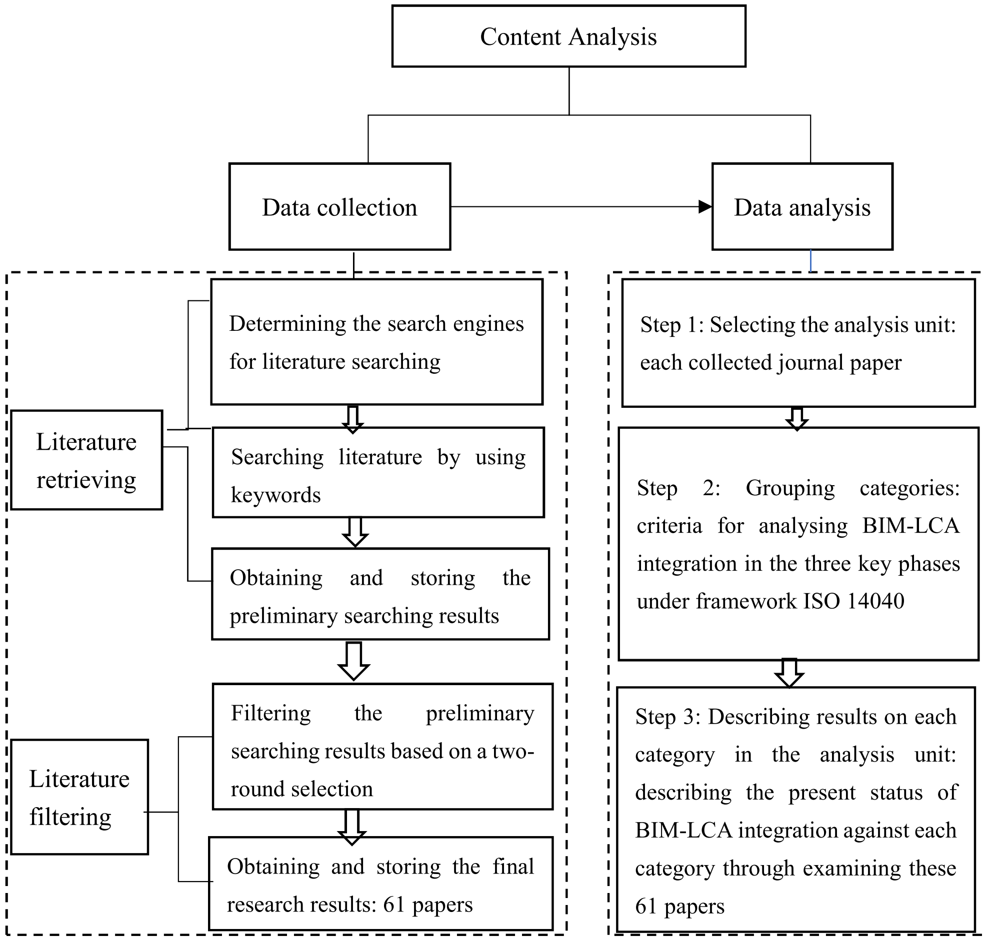


Fig. 3. Procedures of conducting content analysis in analysing the present status of BIM-LCA integration.

2.2.1. *Data collection*

Data collection refers to searching and identifying adequate BIM-LCA integration-related publications from academic databases, which comprises methods for retrieving and filtering literature.

Literature retrieving starts with determining the search engines. The scholarly publication search engines, Scopus and Web of Science were chosen for literature searching in this study as they cover critically influential abstract and citation databases in engineering and technology field [42]. Then, a full search of BIM- and LCA-related papers published in these databases from 2012 to June 2021 was conducted. The key words and phrases used in BIM -LCA integration literature were: (BIM OR “building information modelling” OR “building information model” OR “3D models” OR “information technology”) AND (LCA OR “life cycle assessment” OR “life cycle analysis” OR “environmental impact”). The literature retrieval results are limited to journal articles written in English. There are 662 and 479 journal articles initially obtained from Scopus and Web of Science respectively. Subsequently, by comparing the articles between the two databases and removing the duplicated articles, 618 research articles were selected for further analysis.

The preliminary results were then filtered based on the research purpose, adopting two-round article selection to ensure the filtering quality. In the first–round section, the article title, abstract, and keywords were scanned and checked to identify relevant papers. The filtering rules in this round were: 1) the research objects are building projects, not roads, bridges, or others, and 2) the publications focus on BIM-LCA integration as some articles only mention the concept of BIM-LCA integration. Articles that do not provide information related to the integration processes between BIM and LCA tools were excluded. Accordingly, a total of 104 papers were obtained, which were critically reviewed in the second-round selection. The filtering rule in the second round was the effectiveness in the solutions on BIM and LCA integration. For example, publications that only provide solutions on how to integrate BIM and LCA tools but do not validate the proposed solutions on BIM-LCA integration using case studies or any other method were excluded. In this case, the content extracted from the rest articles should be effective in representing the state-of-the-art of BIM-LCA integration. Ultimately, 61 related articles were retained and included for data analysis (See supplementary data - Appendix A).

2.2.2. *Data analysis*

There are three procedures to carry out data analysis in content analysis method: 1) selecting the analysis unit, 2) grouping categories, and 3) describing the results on each category in the analysis unit [43].

The analysis unit can be words, sentences, phrases, paragraphs, or a whole text [44]. For the selection of analysis unit, the basic principle is to associate with the objective of a study [44]. Seuring and Müller [45] suggested a single article to be an analysis unit to understand the state-of-the-art of a research topic. This is because an article would not be too big or too small, and it can be considered as a whole and as the context of a textual unit during the analysis process [39]. Therefore, the analysis unit in this study is a journal article.

The second procedure is to define categories for analysing the content in each selected analysis unit. Grouping categories can be conducted based on an existing framework or perspective or a self-developed framework [44]. Afore-analysis reveals that the defined six criteria can adequately reflect the performance of BIM-LCA integration in the three key phases under ISO 14040 framework. Therefore, in this research, the six criteria are designed as the categories for analysing the performance of BIM-LCA integration in each analysis unit. Consequently, in line with defined criteria, there are six specific categories, namely 1) LODs of BIM models and LCA data source (Category 1 from LCI phase), 2) data structure and naming convention adopted for data from the BIM model (Category2 from LCI phase), 3) manners of data exchange (Category 3 from LCI phase), 4) environmental impact categories (Category 4 from LCIA phase), 5) ways to present the environmental impacts of a building (Category 5 from LCIA phase), and 6) research topics/goals in BIM-LCA integration studies (Category 6 from interpretation phase) (refer Fig. 2).

Contents of the 61 selected papers were analysed and filtered based on the defined six categories. The results are recorded in spreadsheets (See supplementary data- Appendix A).

3. Present status of BIM-LCA integration under the framework of ISO 14040 standards

As discussed in section 2, the present status of BIM-LCA integration can be analysed by referring to the performance of BIM-LCA integration against each category at LCI, LCIA and interpretation phases.

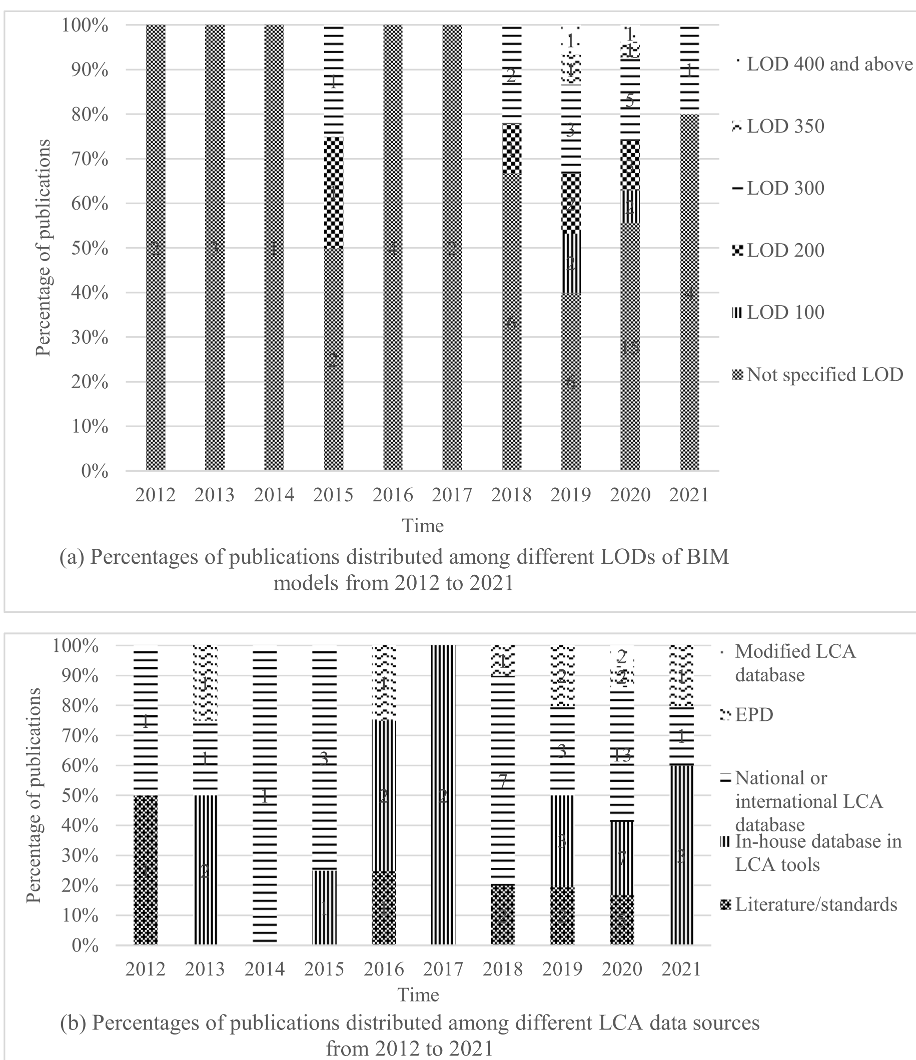
3.1. Performance of BIM-LCA integration at LCI phase

The performance of BIM-LCA integration at LCI phase can be analysed by referring to each criterion under each category for LCI phase (i.e., Category 1, Category 2, and Category 3) against the data presented in literature review. The performance against each criterion under each category in reviewed articles is captured and presented in Figs. 4–6.

3.1.1. Performance of category 1

As shown in Fig. 4 (a), most of the publications on BIM-LCA integration have not declared specific LODs of BIM models, and this finding is consistent with that of Soust-Verdaguer et al. (2017) [9]. Despite that, increasing publications have stated the LODs of BIM models during the past 5 years (from 2017 to 2021). LOD 300 is widely used in research studies compared to LOD 200 and LOD 100 (refer to Fig. 4a) A possible reason for that is LOD 300 has defined the most relevant materials and components for assessing environmental impacts of buildings [9].

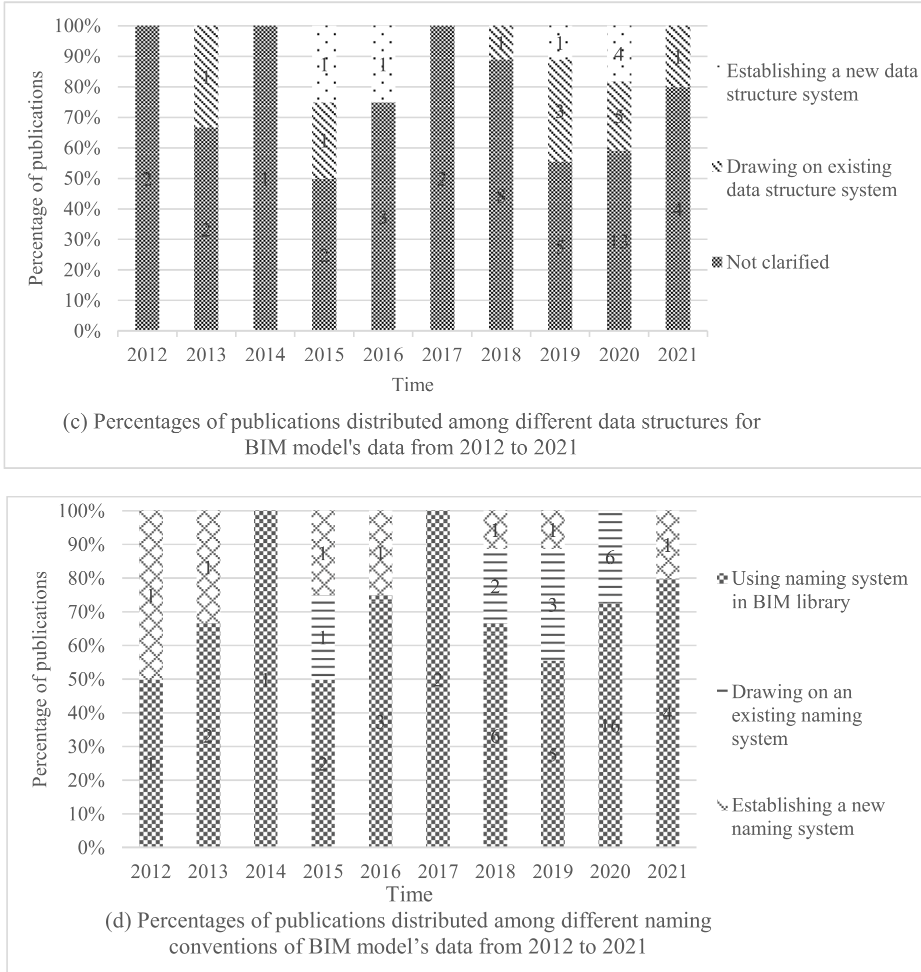
In referring to the LCA data source, as shown in Fig. 4 (b), existing international or national LCA databases are the most popular way to obtain LCA data over the past decade except in 2013, 2016, and 2017. "In-house databases in LCA tools" are the most widely used way in 2013, 2016 and 2017. Environmental product declaration (EPD) has been increasingly adopted in BIM-LCA integration studies since 2018. This result is associated with ISO 21930 standard issued in 2017 that establishes the principles, specifications, and requirements for developing EPDs for construction products and services and thus facilities the application of EPD in environmental impact assessment of buildings [25]. LCA data can also be retrieved from literature or standards. It is



(a) Percentages of publications distributed among different LODs of BIM models from 2012 to 2021

(b) Percentages of publications distributed among different LCA data sources from 2012 to 2021

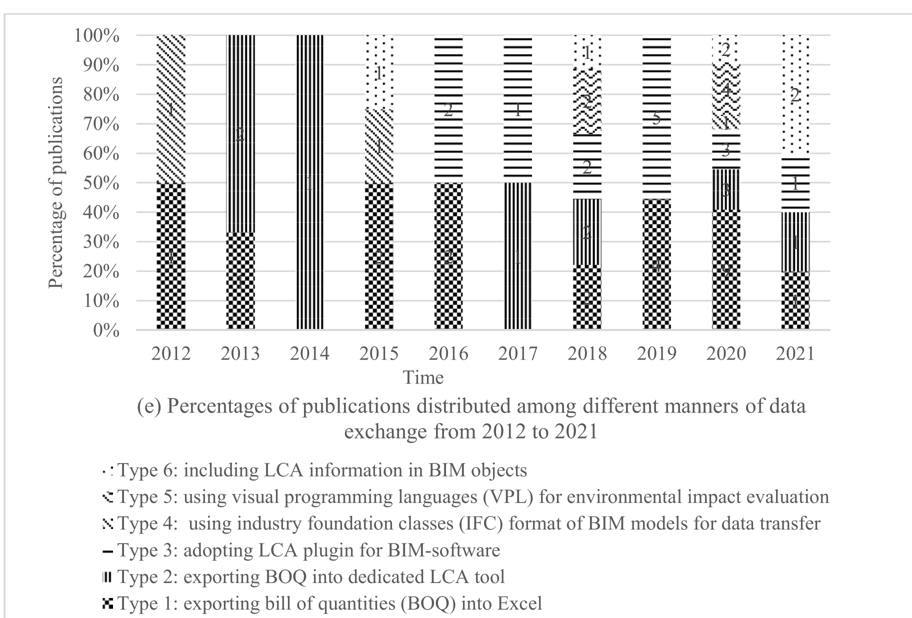
Fig. 4. Performance of BIM-LCA integration against Category 1.



(c) Percentages of publications distributed among different data structures for BIM model's data from 2012 to 2021

(d) Percentages of publications distributed among different naming conventions of BIM model's data from 2012 to 2021

Fig. 5. Performance of BIM-LCA integration against Category 2.



(e) Percentages of publications distributed among different manners of data exchange from 2012 to 2021

Fig. 6. Performance of BIM-LCA integration against Category 3.

worth noting that two studies compiled existing databases (e.g., Ecoinvent database and Inventory Carbon and Energy database) to adapt to Hungarian and Malaysian conditions [46,47].

3.1.2. Performance of category 2

Having examined the data structure of BIM materials in previous BIM-LCA integration studies, there are two methods to address the data structure for materials in BIM: 1) drawing on existing data structure systems (e.g., the Swiss building element classification scheme for cost estimation EBKP-H), and 2) establishing new data structure systems. It can be seen from Fig. 5 (c), drawing on the existing data structures is more popular than establishing a new data structure for BIM materials. A possible explanation may be the existence of many mature construction classification systems such as Uniclass and Onimiclass. Overall, although a couple of studies have attempted to unify the data structure between BIM materials and LCA data by using existing data structures or establishing new data structures [4,48,49], most of the collected publications have made no efforts in this aspect. This implies that the process of mapping data from the BIM model to LCA data tends to be indistinct and ambiguous so far.

In referring to naming conventions for the objects in BIM models, (refer to Fig. 5 (b)), most papers directly use the default naming of building materials in BIM library without unifying the names between BIM materials and LCA data. There is one publication per year establishing a new naming system for BIM materials and LCA data over the past decade, except 2014 and 2017 (refer to Fig. 5b). Despite that, the total number of publications establishing a new naming system is less than that of drawing on existing naming systems. Interestingly, this research finding is similar to that of data structure for BIM models in Fig. 5 (c). This is because the existing classification systems have provided naming codes for BIM materials and LCA data, contributing to wider use of existing systems than that of new systems.

3.1.3. Performance of category 3

As discovered in Section 2, there are six types of approaches for exchanging data between BIM materials and LCA data. According to Fig. 6, type 1 (exporting bill of quantities (BOQ) into Excel) and type 2 (exporting BOQ into dedicated LCA tools) are the most popular BIM-LCA integration methods for exchanging data between BIM and LCA tools during the period of 2012–2020. This finding is consistent with that of the study by Obrecht et al. (2020) that argued BIM and LCA integration via BOQ was the most adopted approach. Next to type 1and type 2 approaches, type 3 (adopting LCA plugins for BIM software) has been widely used since 2016 (refer to Fig. 6). A possible reason is that Tally has been increasingly acknowledged by academia given its user-friendly interface since its release in 2013 [50]. Although type 5 (using VPL for environmental impact evaluation) first appeared in 2018, more and more studies used this approach to exchange data between BIM and LCA tools. The first research developing an approach to include LCA information in BIM objects (type 6) was conducted by Lee et al. (2015). Afterwards, type 6 is widely regarded as an advanced and promising approach and a couple of studies have attempted to include LCA data in BIM models, but relevant research remains scarce (6 publications in total). Nevertheless, type 6 has been increasingly adopted in recent research studies on BIM-LCA integration. Similar to type 6, type 4 (using IFC format of BIM models for data transfer) has also been rarely used to exchange BIM data with LCA data over the past decade with only3 publications in total.

3.2. Performance of BIM-LCA integration at LCIA phase

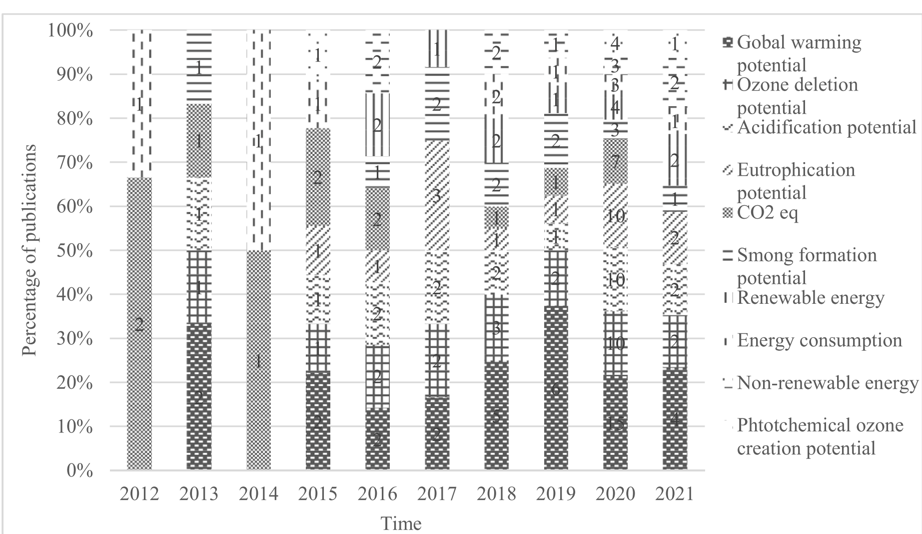
The performance of BIM-LCA integration at LCIA phase can be analysed by referring to the categories for LCIA phase defined in section 2 against the data presented in literature review. The performance against each criterion under each category (Category 4 and Category 5) in reviewed articles is captured and presented in Figs. 7 and 8.

3.2.1. Performance of category 4

There are over 20 indicators used to express environmental impacts of buildings. According to Fig. 7, increasing number of environmental impact indicators are adopted in studies during the period of 2012–2020, with two indicators used in 2012 and ten used in 2020. The most frequently used major environmental impact indicator is GWP (refer to Fig. 7). This coincides with the research study conducted by Soust-Verdaguer et al. [9].

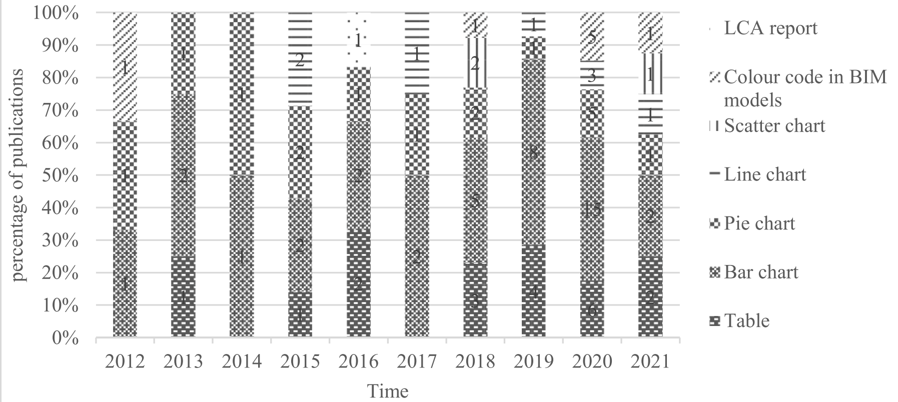
3.2.2. Performance of category 5

There are seven ways to present environmental impacts of buildings: 1) tabulated format, 2) bar chart, 3) pie chart, 4) line chart, 5) scatter chart, 6) colour code in BIM models and 7) LCA report. According to Fig. 8, despite the application of BIM in life cycle assessment, only 8 publications write back the environmental impacts to BIM models for 3D



(f) Percentages of publications distributed among different environment impact indicators from 2012 to 2021

Fig. 7. Performance of BIM-LCA integration against Category 4.



(g) Percentages of publications distributed among different ways to present LCA results in each reviewed article

Fig. 8. Performance of BIM-LCA integration against Category 5.

visualization by colour-coding the building elements in the past decade. Most studies present the environmental results in traditional ways such as bar charts and pie charts. Bar chart is the most popular adopted in about 60% of the reviewed publications from 2012 to 2021.

3.3. *Performance of BIM-LCA integration at interpretation phase*

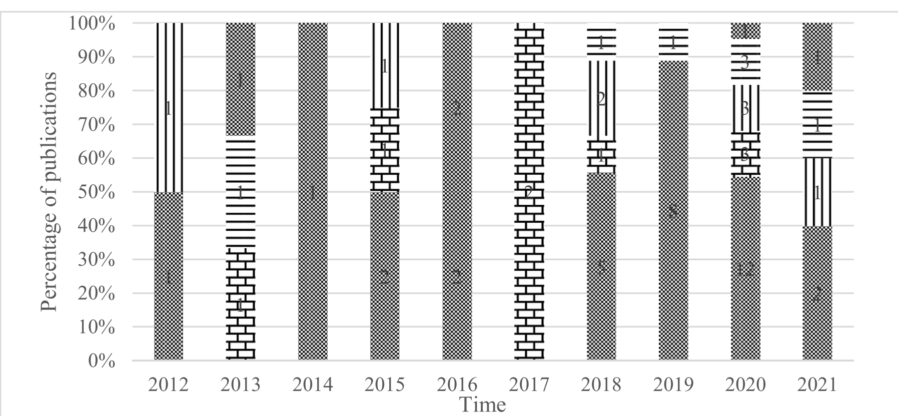
The performance of BIM-LCA integration at interpretation phase can be analysed by referring to each identified research topic/goal (refer Category 6) against the data presented in reviewed publications. By examining the research goals and content in reviewed articles, the research topics/goals for BIM-LCA integration studies are clustered into five types, namely: 1) identifying hotspots of the environmental impacts of a building, 2) comparing design alternatives, 3) conducting sensitivity analysis, 4) carrying out parametric design, and 5) improving BIM-LCA integration approaches. The performance of each research topic (under Category 6) in reviewed articles is captured and presented in Fig. 9.

3.3.1. *Research topic 1: comparing design alternatives*

The purpose of applying BIM-LCA integration in comparing design alternatives (topic 1) is to decide the most suitable design solution or to improve building designs. According to Fig. 9, research on topic 1 accounts for over half of the BIM-LCA integration studies from 2012 to 2021. This is because this research topic covers a wide range of subtopics, such as the comparison among different LODs [48], different building material types [51], different building structural systems [47], and different construction methods [10]. Papers on this topic have been drastically increased since 2018, which indicates more and more attention has been paid to the selection and improvement of design solutions of a building.

3.3.2. *Research topic 2: identifying hotspots of the environmental impacts of a building*

Research into "identifying hotspots of the environmental impacts of a building" (topic 2) aims to evaluate the extent to which building components have environmental impacts over its life cycle. With the hotspot analysis results, strategies on design optimization are created to control and reduce carbon emission and energy consumption caused by building components with significant environmental impacts [35,36]. Hotspots analysis has often been conducted for providing design guidance at early design stages of buildings. As shown in Fig. 9, publications on topic 2 are responsible for the second-largest share among



(h) Percentages of publications distributed among different research topics from 2012 to 2021

Research Topic 5: Conducting sensitivity analysis
Research Topic 4: Improving BIM-LCA integration approaches
Research Topic 3: Carrying out parametric modelling
Research Topic 2: Identifying hotspots of the environmental impacts of a building
Research Topic 1: Comparing design alternatives

Fig. 9. Performance of BIM-LCA integration against Category 6.

publications regarding BIM-LCA integration over the past decade. It can also be seen from Fig. 9 that hotspots identification has been getting steady attention of researchers since 2017 because it has become an important way to assist decision makers to reduce the environmental impacts and optimize the design of a building.

3.3.3. Research topic 3: carrying out parametric modelling for optimal design

Parametric modelling refers to defining the building geometry, building services, and boundary conditions with mathematical formulae [52]. Once the parametric model of a building has been created, the building can be quickly and easily modified by varying the parameters. According to Fig. 9, similar to topic 2, there are a total of 8 papers on topic 3 (carrying out parametric modelling for optimal design) from 2012 to 2021. However, there are only 2 papers on topic 3 from 2012 to 2017. After 2017, an increasing number of papers have been published on this topic. This suggests that researchers have paid more attention to this topic and parametric modelling is likely to be a promising tool for building design in future.

3.3.4. Research topic 4: improving BIM-LCA integration approaches

The main purpose of the research studies attributed to topic 4 (improving BIM-LCA integration approaches), is to solve the issues of information shortage in building materials in the early design stages [32] or determine the optimal design solutions based on the multi-objective optimization of building design [51]. As shown in Fig. 9, it is interesting to see that in the follow-up period of 4 years after the publication by Kulahcioglu et al. [53], no papers on topic 4 were published. However, from 2018 onwards, many research studies developed new BIM-LCA integration approaches. Although there are few papers on topic 4 (7 papers), a rapidly growing interest in developing BIM-LCA integration approaches has been detected, which implies that this topic will continue to be a hot research interest in future.

3.3.5. Research topic 5: conducting sensitivity analysis

Sensitivity analysis in BIM-LCA integration studies (topic 5) is often carried out to test the impact levels of different building design variables on the building performance, filtering out the most influential design variables. Highly sensitive design variables will be further analysed to provide design guidance and to assist make appropriate choices among design alternatives [54]. It can be seen from Fig. 9, research into topic 5 has been increasing since 2013, but the total number of related papers is relatively small (6 papers). This reveals that although this topic has been receiving attention from researchers, more efforts should be devoted to the development of sensitivity analysis based on BIM-LCA integration.

4. Discussion

Above research results have revealed the present status of research into BIM-LCA integration using ISO 14040 framework. However, some unaddressed issues in BIM-LCA integration are identified from the research results. These issues may hinder the further development of BIM-LCA integration in building sector if they are not properly addressed. Therefore, this section discusses the research results from

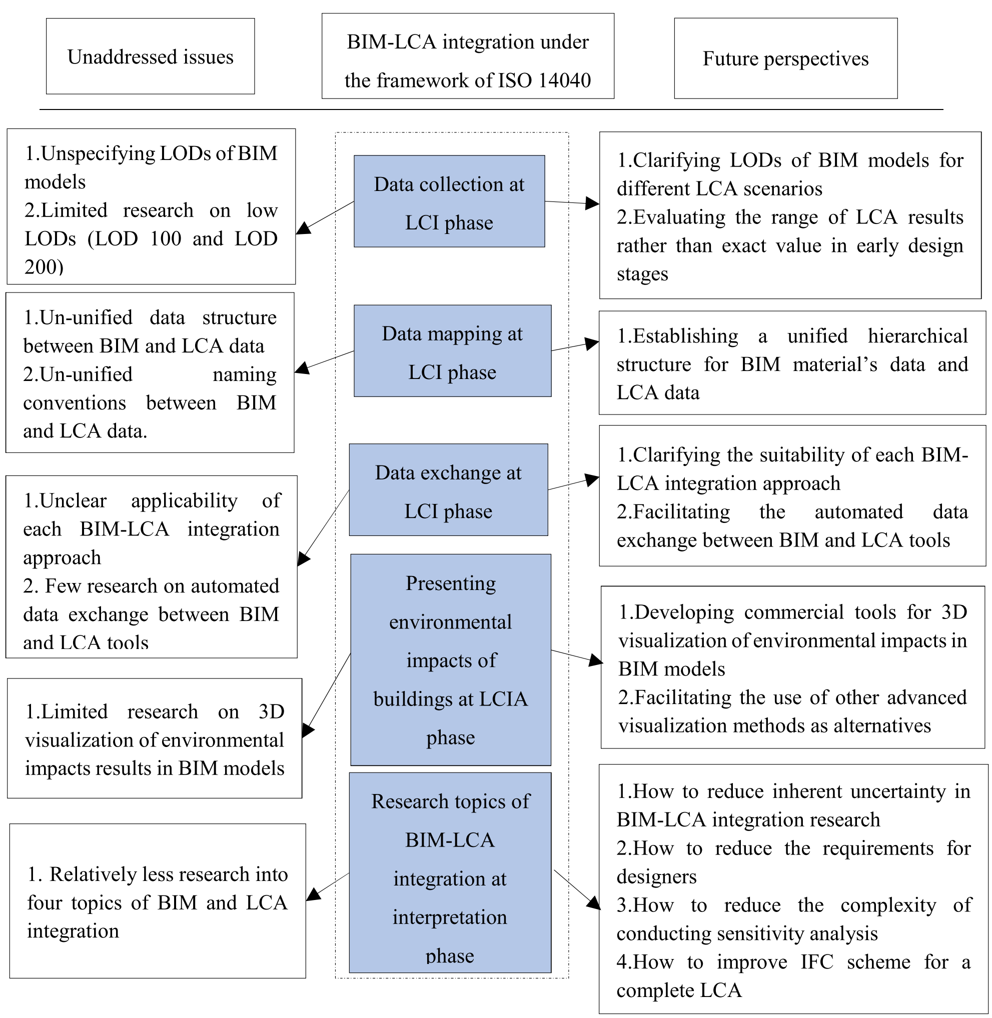


Fig. 10. Unaddressed issues and future perspectives in BIM-LCA integration.

two aspects: 1) some notable unaddressed issues in BIM-LCA integration, and 2) future perspectives on improving BIM-LCA integration in line with the identified unaddressed issues, as illustrated in Fig. 10. Section 4.1 provides a detailed explanation on these unaddressed issues.

4.1. Unaddressed issues and future perspectives in BIM-LCA integration at LCI phase

The unaddressed issues at LCI phase are discussed by referring to the performance of BIM-LCA integration against Category 1, 2, and 3.

4.1.1. Unaddressed issues and future perspectives in the accessibility of BIM model's data

According to the performance of Category 1 given in section 3, there are two notable unaddressed issues. The first issue is that the research efforts on the accessibility of data from the BIM model have not been well presented in BIM-LCA integration studies. A possible reason is the lack of a standardized definition of LODs of BIM models in LCA implementation. The second issue in Category 1 is that limited BIM-LCA integration research has focused on LOD 100 or LOD 200 of BIM models. This may arise from the information shortage at the early design stages of buildings [5].

To address the two issues identified in Category1, the following two measured needs to be explored in future work for providing solutions namely 1) defining LODs of BIM models for different LCA scenarios, and 2) evaluating the range of LCA results instead of exact value in early design stages.

4.1.1.1. Defining LODs of BIM models for different LCA scenarios. Limited studies have been conducted to investigate the required LODs of BIM models in different LCA implementation scenarios (e.g. screening LCA, simplified LCA), even though each LCA scenario has unique needs for the richness levels of information regarding buildings [9]. Given the lack of standards that can provide a reference for specifying LODs in BIM-LCA integration studies, a promising research direction is to create a standard that defines suitable LODs of BIM models in accordance with various LCA scenarios.

4.1.1.2. Evaluating the range of LCA results instead of exact value in early design stages. To solve the issue of information shortage on building materials in early building design stages especially in low LODS such as LOD 100 and LOD 200, many studies calculate the LCA results of building materials by using default values in BIM library [55], average values of standard materials [5], or placeholders for unclear building materials [32]. However, the LCA calculation results of building materials were overestimated or underestimated in these studies. Given the fact that information about building elements is available in low LODs [56], this study suggests calculating the range of LCA results of building elements instead of the exact LCA value of building materials in early design stages. The range of LCA results in early design stages can also support the decision-making of building designs, as shown by Gervásio [56]. Consequently, research on how to evaluate the range of LCA results in early design stages can be a promising research direction.

4.1.2. Unaddressed issues and future perspectives in the structure of data from BIM model

Performance of Category 2 reveals that most studies fail to unify the data structures between BIM and LCA data, potentially resulting in inaccurate LCA results for buildings. This is because the quantity of given construction material is aggregated into the quantity of composite materials calculated using quantity taking off tools in BIM software [57]. As a result, if the composite material data extracted from BIM models has not been disaggregated into individual construction materials prior to assigning the extracted BIM data into LCA data, it will lead to errors in LCA results for buildings.

Establishing a hierarchical data structure for BIM data in order to align with LCA data is critical. Furthermore, unified naming conventions can be established to make it easier to link BIM data with corresponding LCA data. In this regard, although various attempts have been made in a couple of studies to solve this problem [58,59], a standardized structure of BIM materials and LCA data should be proposed. Future research on "how to create a unified data structure and naming convention" is therefore important.

4.1.3. Unaddressed issues and future perspectives in the manners of data exchange

Although research findings of Category 3 reveal that "exporting BOQ into Excel" is the most common method to exchange data between BIM and LCA tools, we cannot conclude that "exporting BOQ into Excel" is better than other BIM-LCA integration approaches. This is because the applicability ranges of these approaches vary between various LCA scenarios. For example, Tally (an LCA plugin for BIM software) is a viable choice for evaluating the environmental impact of a building in the early design stages, but the evaluation results from Tally would not be precise enough in the detailed design stages [3]. Nevertheless, limited research efforts have been done to explore the applicability of each BIM-LCA integration approach.

Another issue related to data exchange between BIM and LCA tools is that most studies adopt manual BIM-LCA integration approaches, such as "exporting BOQ into Excel" and "exporting BOQ into dedicated LCA tools". Data transfer from BIM model to LCA tools depends on manual work in these studies, and this process may cause some unexpected errors, such as information loss of building materials and deviation of BIM models.

To improve the data exchange between BIM and LCA tools, two research directions are worth noting, namely 1) clarifying the suitability of each BIM-LCA integration approach in different LCA scenarios and 2) facilitating the development of automated data exchange between BIM and LCA tools.

4.1.3.1. Clarifying the suitability of each BIM-LCA integration approach in different LCA scenarios. Although environmental impact assessment of a building can be performed by six types of BIM-LCA integration approaches, choosing inappropriate approaches may lead to ineffective LCA results [34]. It is important to develop methods for LCA practitioners to identify and select suitable BIM-LCA integration approaches for different LCA scenarios easily. Consequently, it is considered important to examine the suitability scopes of each BIM-LCA integration for various LCA scenarios in future.

4.1.3.2. Facilitating the development of automated data exchange between BIM and LCA tools. To reduce human errors in data transfer process, automated data exchange methods in BIM-LCA integration approaches have been highlighted by many studies [9,60]. However, the poor interoperability between BIM and LCA tools makes the automated interaction between both tools difficult. Therefore, more advanced techniques may need to be developed to facilitate the automated integration between BIM and LCA tools.

4.2. Unaddressed issues and future perspectives on BIM-LCA integration at LCIA phase

The unaddressed issues at LCIA phase are discussed by referring to the performance of BIM-LCA integration against Category 5.

The performance of BIM-LCA integration at LCIA phase indicates that research into using colour codes in BIM models for 3D presentation of environmental impacts from buildings is very limited, even though it has been widely acknowledged as an advanced method of presenting environmental impacts of buildings [55]. A possible explanation is that the lack of commercial tools for colour code visualization hinders presenting environmental impacts of a building in a 3D visualization manner [22]. Considering the limited research efforts on 3D visualization of environmental impacts of a building in BIM models, two measures can be proposed; 1) developing commercial tools for 3D visualization of environmental impacts in BIM models and 2) facilitating the use of other advanced visualization methods as alternatives.

4.2.1. Developing commercial tools for 3D visualization of environmental impacts in BIM models

Currently, there are few studies using programming languages to embed environmental impacts into BIM models. To make it more accessible to LCA practitioners to present the environmental assessment results in an intuitive and visualised way, more efforts should be put into developing commercial tools.

4.2.2. Facilitating the use of other advanced visualization methods as alternatives

The use of other advanced visualization methods is considered as an alternative to colour code visualization [35]. Virtual reality, for instance, offers a more intuitive way to visualise the environmental impacts of building elements and improves the communication of LCA results among stakeholders [61,62]. Nevertheless, research into advanced visualization methods is very limited, and there is still much room to explore new visualization alternatives for presenting LCA results in an intuitive and visualised manner.

4.3. Unaddressed issues and future perspectives on BIM-LCA integration at interpretation phase

The performance of BIM-LCA integration at interpretation phase has revealed that relatively less research effort has been devoted into research topics 2, 3, 4, and 5, even though they have made great contributions to the decision-making and optimization of building design. Future research directions are proposed to address to cater the challenges in the four topics.

In research topic 2 (identifying hotspots of the environmental impacts of a building), the effectiveness of hotspot identification can be affected by the inherent uncertainty of integration between BIM and LCA tools. The uncertainty of BIM-LCA integration due to the imprecision of BIM models, the uncertainty of BIM data input, and data variability results in inaccurate quantities of building materials and correspondingly ineffective LCA results [35]. Consequently, the results of hotspot identification appear to be less effective. Therefore, it is essential to improve the precision of BIM models and eliminate the risk of BIM data input ambiguity. In other words, “how to reduce inherent uncertainty in BIM-LCA integration” deserves more attention in future.

In referring to topic 3 (parametric modelling for building design), there are two key issues. First, similar to the challenges in topic 2 (identifying hotspots of the environmental impacts of a building), the inherent uncertainty of BIM-LCA integration has a significant impact on the accuracy of LCA results calculated by parametric modelling approaches [35,63]. Second, parametric modelling approaches are considered to be more sophisticated than other simplified LCA tools in conducting LCA since the practitioners should know some visual programming language knowledge when using parametric modelling approaches [63]. The high demands on professional knowledge make parametric modelling tough for designers. Therefore, in addition to reducing the inherent uncertainty of BIM-LCA integration, more research should be done to find solutions to reduce the requirements for designers. For example, developing advanced tools to simplify relevant work could be examined in future.

Conducting sensitivity analysis (topic 4) in BIM-LCA integration research faces two challenges: 1) the high need for designers to understand knowledge on probability distributions of unknown parameters, and 2) the complexity combining sensitivity analysis with BIM-LCA integration process [64]. As a result, limited studies have carried out sensitivity analysis in BIM-LCA integration studies. To enrich the knowledge in this topic, there is a pressing need to develop new tools to simplify sensitivity analysis in BIM-LCA integration. Future research should put more efforts on “how to reduce the complexity of conducting sensitivity analysis in BIM-LCA integration research”.

As for topic 5 (improving BIM-LCA integration approaches), although many studies have emphasised the fully-automated approach “including LCA information into BIM objects”, this approach necessitates much superior hardware in order to handle an enormous amount of data [19,34]. A feasible solution to deal with a significant amount of data is to use IFC scheme for storing LCA-related information within BIM environments [15]. However, IFC attributes in the latest IFC4 scheme are only available for conducting a simplified LCA, and not for a complete LCA [15]. Given this fact, if a complete LCA is required, more IFC attributes should be developed. Therefore, to further develop BIM-LCA integration approaches, related BIM organizations should put more efforts into “how to improve IFC scheme for providing abundant LCA information”.

5. Conclusion

This research examined the present status of the integration between BIM and LCA using ISO 14040 framework. This research study reviewed 61 research papers from 2012 to 2021. The results indicated that at LCI phase, BIM-LCA integration studies have been well presented in LCA data collection but have poor accessibility for data from the BIM model. The data structures for data from the BIM model data and LCA data have not been unified yet. Moreover, manual data exchange is the main method used for data transfer from BIM to LCA tools. At LCIA stage, environmental impacts of buildings are mainly presented in traditional ways such as bar charts, pie charts and tabulated formats. The findings from this study also revealed majority of BIM-LCA integration studies have been adopted for comparing design alternatives at interpretation phase.

The recommendations of this study for future work can be provided for BIM and LCA related organizations/practitioners, construction industry, and for academia separately. For BIM- or LCA-related organizations/practitioners there are three recommendations namely; 1) a standard defining suitable LODs of BIM models in accordance with various LCA scenarios should be created, 2) a standardized data structure for BIM materials and LCA data should be proposed, and 3) more IFC attributes should be developed for a complete LCA. It is recommended that the construction industry should: 1) put more efforts to develop commercial tools for presenting LCA results in an intuitive and visualised way, 2) develop advanced tools to simplify parametric modelling and sensitivity analysis for BIM-LCA integration and 3) develop more advanced techniques to facilitate the automated integration between BIM and LCA tools. For academia, this research recommends to 1) initiate more research efforts on evaluating the range of LCA results for building elements in early design stages; 2) to develop strategies for LCA practitioners to select the most suitable BIM-LCA integration approaches for different LCA scenarios, and 3) to conduct research to improve the precision of BIM models and eliminate the risk of BIM data input ambiguity. The research results revealed in this study are valuable to both researchers and practitioners. They are allowed to have a comprehensive and systematic understanding of the present status of BIM-LCA integration and guide future work in improving the integration between BIM-LCA integration. Nevertheless, it is appreciated that two mainstream search engines referred to in this study may not contain all related publication works. It is recommended for future research to include more related articles retrieved from other search engines for further analysis.

CRediT authorship contribution statement

Vivian WY. Tam: Supervision. **Yijun Zhou:** Methodology, Data curation, Conceptualization, Writing – original draft. **Chethana Illankoon:** Writing – review & editing. **Khoa N. Le:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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