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A REVIEW ON LIFE CYCLE COST ANALYSIS OF BUILDINGS BASED ON BUILDING INFORMATION MODELING

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Abstract. Life cycle cost analysis (LCCA) plays an essential role in the economic sustainability assessment of buildings, and building information modeling (BIM) offers a potentially valuable approach to fulfilling its requirement. However, the state of LCCA based on BIM is unclear despite previously published works. Therefore, this paper aims to address this gap by reviewing 45 relevant peer-reviewed articles through a systematic literature search, selection, and assessment. The results show that three data exchange methods integrate BIM and LCCA through data input, calculation, and output. Precision management, optimization measures, and parameter analysis through BIM significantly improve the value of buildings. Also, a methodological framework is summarized that combines LCC with other indicators based on BIM to consider economic, environmental, and social impacts, which can be monetized to assess life cycle sustainability costs. These findings provide insights for scholars and practitioners.

Keywords: life cycle cost analysis, whole life cost, building information modeling, life cycle assessment, economic sustainability assessment, literature review.

Introduction

As a vital part of triple bottom lines for life cycle sustainability assessment (LCSA) (Klöpffer, 2003; Kloepffer, 2008), life cycle cost analysis (LCCA) has a key effect on a building's life cycle economic assessment. LCCA can evaluate the economic performance of a construction project throughout its life cycle during its design phase, which is conducive to optimizing cost performance. Among the most critical drivers of construction industry change, using LCCA in assessing project proposals has been identified as one of the most important elements (Manoliadis et al., 2006). Recently, the use of LCCA has been rapidly increasing in the construction industry (Goh & Sun, 2016), since LCCA-based decision-making can benefit building design, construction, and operation (Kirkham, 2005).

In the history of LCCA, many practical difficulties have limited its widespread application from the beginning. Cole and Sterner (2000) pointed out that there has been a wide gap between the theory and practice of LCCA. In other words, although the concept of LCCA is widely recognized, it has not been widely used in engineering practice (Goh & Sun, 2016). The main reason is that the process of LCCA requires a lot of time and effort (Jansen et al., 2020).

Building Information Modeling (BIM), a virtual 3D model with information, plays an important role in reducing time and effort, increasing productivity, and saving as a data tool for construction management (Barlish & Sullivan, 2012; Bryde et al., 2013). Reducing time and

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human error is often regarded as the main benefit of BIM adoption (Soust-Verdaguer et al., 2017), making LCCA convenient and stable for adoption. Additionally, BIM can greatly facilitate the automatic quantification of required inputs for LCCA, as it can automatically generate the bill of quantities (quantity take-off) used in buildings (Choi et al., 2015). Moreover, energy consumption simulation based on BIM also helps calculate operational costs (Mahiwal et al., 2021). These findings show that BIM is of great help to LCCA.

Realizing the value of LCC is more important than reducing LCC (Elhegazy, 2020). BIM can avoid ineffective costs, which is beneficial for realizing the value of money in cost management (Fazeli et al., 2019). Based on the finance-first approach, the life cycle sustainability assessment (LCSA) framework, a popular sustainability model for the triple bottom line (TBL), is introduced to take environmental, social, and financial outcomes into account (Klöpffer, 2003; Kloepffer, 2008). For a successfully sustainable building, other metrics are just as important as LCC, and BIM may be an effective way to integrate LCC and other indicators (Llatas et al., 2020).

Because of the importance of BIM in LCCA, many researchers have gained achievements in this topic. However, despite a certain amount of previously published works, the state-of-art LCCA based on BIM is still vague because a systematic review about this is unavailable. Specifically, some research questions in existing research remain limited:

(1) What is the current status of BIM-based LCCA research?
(2) What are the data process and exchange methods in calculating LCCA based on BIM?
(3) How to use BIM to realize the value of LCC in buildings by accuracy control, optimization measure, and parameter analysis?
(4) What are the methods for integrating, comparing, and optimizing LCC with other indicators based on BIM?

This study aims to address these gaps by reviewing the relevant peer-reviewed papers. Through the review of this paper, scholars can understand the state-of-art BIM-based LCCA research, find the benefits and barriers of the current situation, and find future research directions. In addition, this review can also help the development of next-generation BIM-based LCCA software to realize the value of cost in combination with other metrics in the industry application.

Apart from the introduction, Section 1 describes the brief background and concept for LCCA and BIM. Then, the methodological framework of this review is provided in Section 2. Section 3 gives descriptive results on the current research status. In Section 4, the topics about BIM-based LCCA are divided, and each topic is discussed in depth. Section 5 analyzes the shortcomings of existing research and points out future research directions. Finally, the conclusions summarize the main results of this review.

1. Literature review

This section reviews the concept and fundamental background of LCCA and BIM. Then, the integration of BIM and life cycle is further reviewed, illustrating existing research gaps.

1.1. Life cycle cost analysis

Life cycle cost analysis (LCCA), also called life cycle costing, is the methodology for the systematic economic evaluation of life cycle cost (LCC) (International Organization for Standardization [ISO], 2017). The LCC of buildings is the sum of the costs from each life cycle stage of buildings (Goh & Sun, 2016; Almeida & De Freitas, 2016; Mirzadeh & Birgisson, 2016). ISO 15686-5 (ISO, 2017) divided LCC into four parts, namely construction, operation, maintenance, and end-of-life costs (ISO, 2017). Based on LCC, whole life cost (WLC) involves all high and relevant initial and future costs and benefits of an asset, including LCC, non-construction cost, income, and externalities (ISO, 2017). It is worth noting that the boundary of LCC is not static and can be increased or decreased according to the actual situation. Additionally, EN 16627 (British Standards Institution [BSI], 2015) also provides another popular boundary of LCC.

Although ISO 15686-5 (ISO, 2017) and EN 16627 (BSI, 2015) provide detailed boundaries of LCC, the methodology of LCCA has not been unified in the construction field (Babashamsi et al., 2016; Moins et al., 2020). Although these methods are different, the methodological framework of LCCA typically follows the five parts (Christensen et al., 2005; Li et al., 2019): (1) boundary definition: defining the goal, scope, and boundary according to customer needs; (2) Assumption establishment: establishing the basic assumptions of life cycle period, discount rate, and technically feasible options; (3) Calculation: calculating LCC by summing costs from different life cycle stage and discounting them to the present; (4) Result analysis: selecting economic indicators, such as the payback period, net present value, savings-to-investment ratio, and carrying out analysis, including sensitivity analysis, uncertainty analysis, and risk analysis; (5) Response: reassessing and reevaluating strategies for the selection of favorite options.

1.2. Building information modeling

Building information modeling (BIM), a 3D data tool for construction management (Zhang et al., 2021), is defined as a shared digital representation of a built object that generates a systematic approach to manage critical information and form a reliable basis for decision making throughout its life cycle (Santos et al., 2017; Olawumi et al., 2017). Some mature BIM modeling software is widely used in the market (Barlish & Sullivan, 2012; Bryde et al., 2013; Zhang et al., 2021), such as Autodesk Revit and Graphisoft ArchiCAD.

The most popular BIM standards are by an international OpenBIM organization BuildingSMART (2021), mainly including four basic standards: (1) Industry Foundation Classes (IFC) for data standard; (2) Information delivery manual (IDM) for process standard; (3) International framework for dictionaries (IFD) for standard library; (4) Model view definition (MVD) for process translation (Lai et al., 2019; Lai & Deng, 2018). Additionally, Omniclass (Construction Specifications Institute [CSI], 2021), combining line classification with face classification, is a popular standard for life cycle coding.

The accuracy of BIM is defined by the Level of Development/Detail (LOD) according to the American Institute of Architects [AIA] (2007). The LOD standard contains five levels: LOD 100 is the lowest for graphical and embedded information, and LOD 500 is the highest (Graham et al., 2018). The change of LOD with the design process for different construction categories is shown in Figure 1 (adapted from Cavalliere et al., 2019).

1.3. BIM through life cycle

BIM has been widely used in the life cycle management of buildings (as shown in Table 1). After Eleftheriadis et al. (2017) reviewed research about life cycle energy efficiency based on BIM, more and more review articles focused on the green BIM applications in life cycle environmental impact (Wong & Zhou, 2015; Muller et al., 2019; Crippa et al., 2020). In particular, several reviews related to the integration of BIM and life cycle assessment (LCA) for environmental sustainability (Soust-Verdaguer et al., 2017; Seyis, 2020; Obrecht et al., 2020). Furthermore, Lu et al. (2021) reviewed the integration of LCA and LCC using BIM. Additionally, BIM-based life cycle performance analysis or life cycle sustainability assessment, involving economic, social, and environmental triple bottom lines, are reviewed by Jin et al. (2019) and Llatas et al. (2020). However, the review research about building's economic assessment based on BIM, especially of the LCCA based on BIM, is still unavailable.

2. Materials and methods

A systematic literature review is beneficial to assess the existing research on LCCA based on BIM. The methodology of this literature review is based on the guidance of systematic review frameworks by Lu et al. (2021), Petro et al. (2019), and Antwi-Afari et al. (2019). The review methodology comprises three major steps: literature search, literature selection, and contributions assessment, as shown in Figure 2.

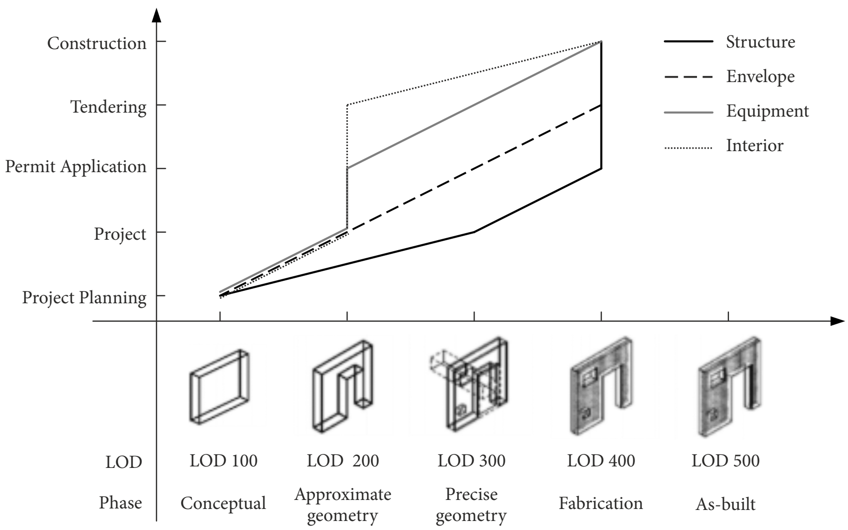


Figure 1. Level of development/detail (LOD) under the design process

Table 1. Relative review papers on BIM applications through the life cycle of buildings

Year	Focus	Financial	Environmental	Social	Reference
2015	Environmental sustainability through green BIM	–	√	–	Wong and Zhou (2015)
2017	Life cycle energy efficiency based on BIM	–	√	–	Eleftheriadis et al. (2017)
2017	BIM–based LCA	–	√	–	Soust–Verdaguer et al. (2017)
2019	Interoperability in green BIM	–	√	–	Muller et al. (2019)
2019	Integrating BIM with building performance analysis	√	√	√	Jin et al. (2019)
2020	Life cycle impact assessment using BIM	–	√	–	Crippa et al. (2020)
2020	Integrating BIM and LCA	–	√	–	Seyis (2020)
2020	BIM and LCA Integration	–	√	–	Obrecht et al. (2020)
2020	Life cycle sustainability assessment during design stages in BIM	√	√	√	Llatas et al. 2020)
2021	Integrating LCA and LCC using BIM	√	√	–	Lu et al. (2021)

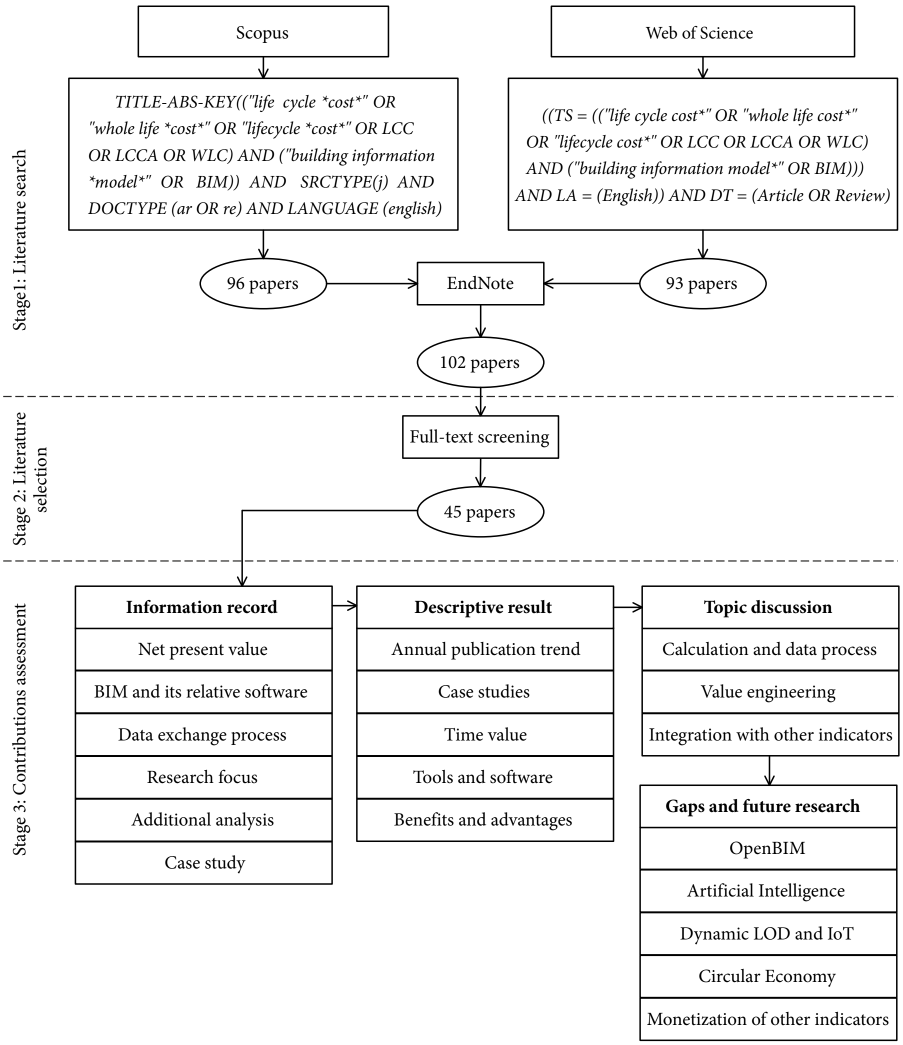


Figure 2. The research framework of this review

2.1. Literature search

The literature was retrieved from two popular academic databases, namely, Web of Science (SCIE, SSCI, A&HCI, ESCI) and Scopus, because both databases are among the largest online academic sources and have a wider coverage of journals and recent publications compared to other search engines (Antwi-Afari et al., 2019; Petro et al., 2019). Moreover, both databases already cover the vast majority of high-quality literature in civil and construction management (Antwi-Afari et al., 2019; Petro et al., 2019). Through retrieval codes shown in Figure 2, Scopus retrieved 96 articles, while Web of Science retrieved 93 until August 2022. Because duplicate articles existed in the original result, all citations from these two databases were exported into EndNote to eliminate duplicate articles. After that, a total of 102 papers were identified.

2.2. Literature selection

Despite using structured retrieval codes, results still included some unsuitable publications that matched retrieval keywords without discussions of LCCA based on BIM. Therefore, the title, abstract, keywords, and conclusion of these publications were read to filter out inappropriate papers further. In this process, studies involving only LCC without actually using BIM or only involving BIM without focusing on LCC were excluded from the scope of this review. In addition, in other construction types, such as roads, bridges, and other infrastructure, the boundary scope of LCC is quite different from that of buildings. This study focusing on buildings also filtered these studies. The screening criteria in this step include:

(1) The article was published in a refereed English journal.
(2) The paper focused on LCCA based on BIM.
(3) The paper only focused on buildings, not roads, bridges, railways, and other construction projects.

Additionally, in the process of full-text screening, potential citations from references should be supplemented to the scope of this review. Fortunately, as the initial search was relatively complete, no new paper was added in this process. Finally, 45 articles about LCCA based on BIM were identified (as shown in Table A1 in the Appendix).

2.3. Contribution assessment

In the final step, these 45 articles were discussed to answer the four questions raised in the introduction. In order to provide data analysis and extraction, the relevant information of each article is recorded in Appendix through the full-text article reading, including: (1) Net present value; (2) BIM and its relative software; (3) Data exchange process; (4) Research focus; (5) Additional analysis; (6) Case study. Then the descriptive results are analyzed by statistical collation of this information, which is written in Section 3. After that, the existing research topics are classified and discussed in depth (Section 4). Finally, potential solutions to existing research gaps are proposed for future research (Section 5).

3. Results

This section analyzes the descriptive results of 45 articles, including their annual publication trends, the distribution of their case studies, the parameter selection of time value, the tools and software used, and the benefits and advantages of integrating LCCA and BIM.

3.1. Annual publication trend

Figure 3 presents the annual contribution of BIM-based building LCCA. Except for one article published in 2007, related research began to flourish in 2014, reaching its peak in 2020 with a rapid rise trend in fluctuations.

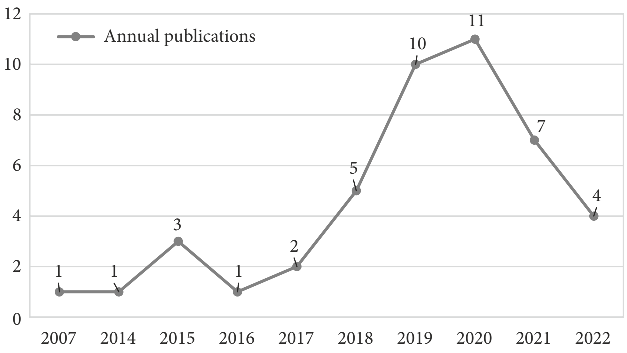


Figure 3. Annual publication trend of BIM-based LCCA

3.2. Case studies

Except for Yung and Wang's (2014) research, almost all studies used case studies to verify their methodology. In these case studies, except for nine articles, most studies determined the service life of buildings and considered service life as a critical factor affecting the outcome of LCC. Of these, 50 years was the most used, followed by 30 years (Figure 4a). These cases involved educational buildings, commercial buildings, residential buildings, and industrial buildings in different countries, as shown in Figure 4b. However, some essential building types, such as medical and agricultural buildings, still have not been studied.

3.3. Time value

Most studies use net present value (NPV) to consider the time value of money of the LCC (shown in Figure 5). Among them, some use the bank rate to reflect the opportunity cost of money for investors, while others use the inflation rate to reflect the increase in the price index. In addition, most studies use the discount rate to consider both interest rate and inflation rate to comprehensively consider the time value of money. The discount rate ranges from 0.0025% to 15%, depending mainly on the local economic development speed and the risk degree (C. Lee & E. B. Lee, 2017). In addition, several studies have compared the effects of different discount rates on LCC results and found the effects to be substantial (Jausovec & Sitar, 2019; Phillips et al., 2020). On the other hand, single present worth (SPW) was applied without consideration of time value if studies only involve the sole stage or different service life in LCCA (Raposo et al., 2019).

3.4. Tools and software

Autodesk Revit held a monopoly of all BIM modeling software and was used in more than three-quarters of these studies (Figure 6a). Compared with BIM modeling software, the energy simulation software, also called Building Energy Modeling (BEM), is used to calculate the operational energy cost, such as Green Building Studio, Ecotect, EnergyPlus, eQUEST, EcoDesigner, and IES VE (Figure 6b).

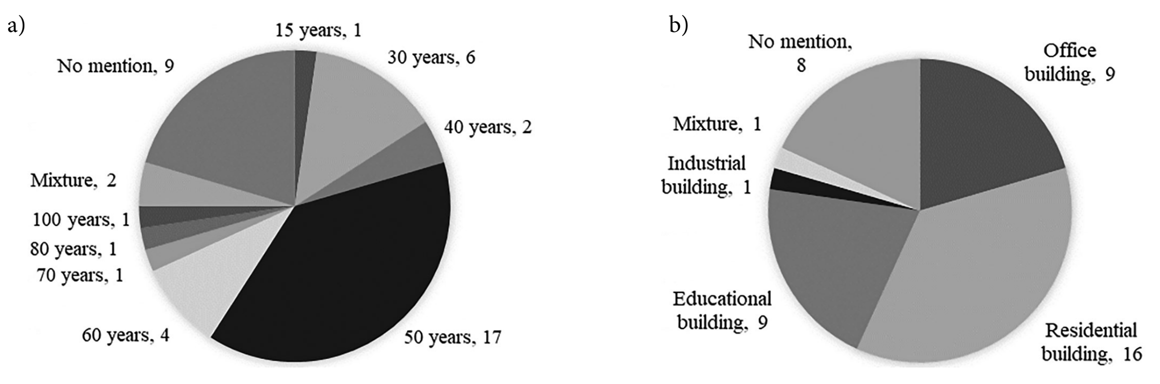


Figure 4. Distribution of service life and building type in case studies: a – service life; b – building type

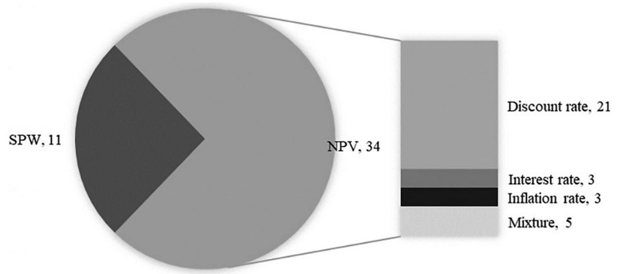


Figure 5. Time value in case studies

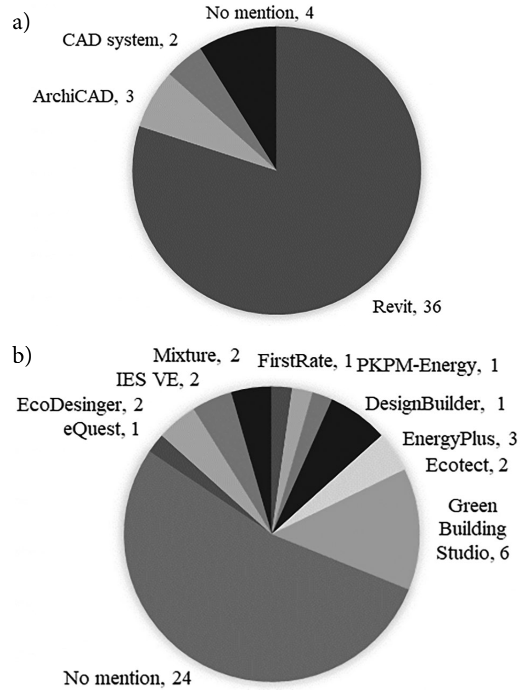


Figure 6. Application of tools and software in case studies: a – BIM software; b – BEM software

For cost software, only Kehily and Underwood (2017) used CostX to calculate the construction cost of buildings, which reflects the scarcity of LCCA commercial software based on BIM.

3.5. Benefits and advantages

Through the summary of the above literature, compared with the conventional LCCA method, BIM-based LCCA has six main advantages, as shown in Table 2. First and foremost, the BIM approach provides valuable and modern support for the LCC calculation (Khodabakhshian & Toosi, 2021; Lee et al., 2020), which is beneficial for reducing labor and time expense (Zhang et al., 2020; Cheng et al., 2022). Secondly, design errors can be checked through BIM modeling, thereby reducing unnecessary costs (Zhuang et al., 2021; Kharazi et al., 2020; Fazeli et al., 2019). Thirdly, the BIM model can quickly update the LCC results of buildings when design changes occur (Pučko et al., 2020). Fourthly, BIM provides a visual expression for LCC results, such as a graphical presentation of information, condition, and spaces, which is convenient for engineers to obtain more intuitive results (Khodabakhshian & Toosi, 2021; Le et al., 2020; Zanni et al., 2019). Fifthly, some BIM-based LCCA studies have transparent and systematic valuation processes (Khodabakhshian & Toosi, 2021), which is conducive to cost auditing. Additionally, BIM provides a shared platform so various stakeholders can work together within a multidisciplinary team (Fu et al., 2007). As a result, users can collect all BIM data accessible to all participants (Pučko et al., 2020).

4. Discussions

This paper identifies three categories for the research interests or applications of BIM-based LCCA papers: 1) Calculation and data process; 2) Value engineering; 3) Integration with other indicators.

4.1. Calculation and data process

Faster, more convenient, and more stable tools have been developed to help the calculation and data process of LCCA based on BIM. For instance, Fu et al. (2007) initially developed an IFC-based LCCA tool. Santos et al. (2019) used the IFC schema to develop IDM/MVD for LCCA. Kehily and Underwood (2017) embedded LCCA in 5D BIM.

In order to help BIM-based LCC calculation, the purpose of this section is to summarize an operative data process methodology, which is divided into three steps: (1) Step 1: data input; (2) Step 2: data calculation; and (3) Step 3: data output. Table 3 shows an example of LCCA based on BIM according ISO 15686-5 (ISO, 2017).

Table 2. Benefits of BIM-based LCCA

No.	Benefits	Ref.
1	Providing modern support for quickly predicting LCC results	Khodabakhshian and Toosi (2021), Lee et al. (2020), Pučko et al. (2020)
2	Reducing the unnecessary costs of buildings in the design phase	Zhuang et al. (2021), Kharazi et al. (2020), Fazeli et al. (2019)
3	Quickly updating the information on buildings to quickly obtain new LCC results	Pučko et al. (2020)
4	Providing visualization expression for engineers to obtain more intuitive results	Khodabakhshian and Toosi (2021), Le et al. (2020), Zanni et al. (2019)
5	Having a transparent and systematic valuation process to cost auditing	Khodabakhshian and Toosi (2021)
6	Supporting collaborative work within a multidisciplinary team	Fu et al. (2007), Pučko et al. (2020)

4.1.1. Data input

According to ISO 15686-5 (ISO, 2017), the boundary of LCC consists of 22 items at construction, operation, maintenance, and end-of-life stages. It is worth noting that the system boundary is not static. It is unnecessary for every item included in Table 3 to be considered, and some additional costs can be supplemented for specific projects. For example, in the research of Vitiello et al. (2019) and Raposo et al. (2019), the cost caused by seismic risk was added to the system boundary of LCC. Based on the system boundary of LCCA, this step includes the following information: 1) the information provided by BIM: BIM not only calculates the bills of quantity quickly but also provides functional area information. 2) the information provided by designers: Quantity surveyors and engineers need to provide external information, such as market price, tax rate, lifespan, and discount rate.

4.1.2. Data process

After obtaining the information in Step 1, formulas are used to calculate the various parts of LCC. Table 3 provides some formulas to process LCC, but these formulas are not defined, and the actual situation may change them in different countries or projects.

There are three main methods for the data exchange process: (1) From BIM to a spreadsheet; (2) From BIM to external software; and (3) Including information in the BIM environment, as shown in Table 4. Method 1 involves exporting BIM information to a spreadsheet, including bills of quantities in the construction, maintenance, and demolishment stage and energy consumption and water consumption at the operation stage. Although this method is clear and transparent in its calculations (Shin & Cho, 2015), error-prone manual calculations are slow because there may be interoperability and compatibility issues between different software (Kim & Park, 2018). Method 2 exports the BIM model to another external software or platform and uses it to calculate LCC. Although this approach reduces manual activity, the incompatibility between external software and the BIM model persists. Method 3 directly connects the external database to the BIM model to complete LCCA in the BIM environment. During this process of Methods 2 and 3, a specific data exchange format is required to ensure the stability and integrity of data, such as Industry foundation classes (IFC) (Fu et al., 2007; Santos et al., 2019; Zanni et al., 2019), Application programming interface (API) (Jalaei et al., 2015; Le et al., 2020; Rad et al., 2021), and COBie (Zanni et al., 2019). Methods 2 and 3 allow users to edit information and update data quickly, but BIM software developers spend a lot of money and time on software development (Santos et al., 2019). Of the three methods, this study recommends Method 3 because it retains the information of LCC in BIM models, while the calculation results of LCC need to be re-assigned to the BIM model in Methods 1 and 2.

4.1.3. Data output

After calculating LCC, its result should be output in an easy-to-understand way. Most studies used tables to describe the results of LCC, and many scholars used bar charts, pie charts, or other charts to describe results vividly. In addition, some researchers (Le et al., 2020; Zanni et al., 2019) have developed visualized BIM-integrated modules to return the LCC results to the BIM model, making the results intuitive.

4.2. Value engineering

Cost management does not mean “the lower, the better” but realizes the value of cost. The application of value engineering can ensure that LCCA-optimized projects are achieved (Usman et al., 2018). As the investment in housing construction/refurbishment will be compensated by reduced energy bills over the life cycle, the value for money is a vital aspect from the outset of a building project in LCCA (Kim & Park, 2018). The Society of American Value Engineers (SAVE) defines value engineering as the systematic application of recognized techniques, the establishment of a value for the function, and the reliable provision of the necessary function at the lowest overall cost (Eqn (1)). The value engineering job plan is divided into pre-study, information, creative, evaluation, development, presentation, and post-study phases (Elhegazy, 2020).

$$\text{Value} = \frac{\text{Function}}{\text{Cost}}. \quad (1)$$

4.2.1. Accuracy management

The accuracy of BIM is defined by the level of development/detail (LOD). In the 45 articles in the Appendix, most studies did not mention the precision of BIM. Nevertheless, LOD 300, a material-level accuracy, is still the most popular (Khodabakhshian & Toosi, 2021; Kharazi et al., 2020; Le et al., 2020). For component-level accuracy, Lee et al. (2020) proposed a method to preliminarily estimate LCC in the early design phase using LOD 100-200.

Figure 7 provides the change of LCC simulation under dynamic LOD of BIM. Up to 80% of the LCC can be influenced by the first 20% of the design process for a building (ISO, 2017), so the concept phase (corresponding LOD 100) is the best time to implement value engineering. Lower LOD is vital for LCC control despite more errors (Jalaei et al., 2015) because it has more opportunities to change design options and vice versa for higher LOD. In short, the accuracy and the potential for value improvement are opposite in LCCA precision management. LOD 300 can provide relatively accurate LCC results and has potential for value improvement, leading to its popularity.

Table 3. Data process method for calculating LCC based on BIM.

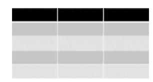
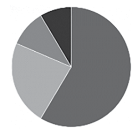
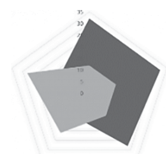
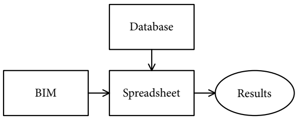
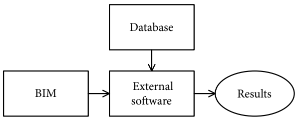
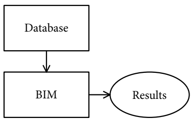
Stage	No.	Step 1: data input		Step 2: data calculation	Step 3: data output
		Provided by BIM	Provided by designers	Example for calculation formula	Visualization types
Construction	Professional fee	FA: floor area (m^2)	PFR_i: professional fee rate for a different type, such as planning fee, design fee, supervision fee	$PF = \Sigma(PFR_i \times FA)$	
	Construction of asset	Q_1: quantity of manual Q_2: quantity of material Q_3: quantity of machinery Q_4: quantity of miscellaneous	CC_1: cost coefficient for manual CC_2: cost coefficient for materials CC_3: cost coefficient for machinery CC_4: cost coefficient for miscellaneous	$CA = \Sigma(Q_1 \times CC_1 + Q_2 \times CC_2 + Q_3 \times CC_3 + Q_4 \times CC_4)$	 Table
	Tax	–	TR_i: tax rate on different classification	$TR_i \times (PF+CA)$	
Operation	Cyclical regulatory cost	FA: floor area (m2) DA: dwelling area (m2)	R_i: different fee rates for rent, insurance, fire, access inspections, property fee, and so on y: the setting of lifespan at the operational stage	$CRC=\Sigma(R_i \times FA+ R_i \times DA) \times y$	 Pie chart
	Energy cost	Q_f: quantity of fuel consumption Q_e: quantity of electricity consumption Q_w: quantity of water and sewerage consumption	CC_f: cost coefficient for fuel CC_e: cost coefficient for electricity CC_w: cost coefficient for water and sewerage y: the setting of lifespan at the operational stage	$EC = \Sigma(Q_f \times CC_f + Q_e \times CC_e + Q_w \times CC_w) \times y$	 Bar chart
	Tax	–	TR_i: tax rate on different classification	$TR_i \times (CRC + EC)$	
Maintenance	Maintenance management	FA: floor area (m2) DA: dwelling area (m2)	R_i: different fee rates for cyclical inspections, design of works, service management, and so on	$MM = \Sigma(R_i \times FA + R_i \times DA)$	
	Refurbishment, Repairs, and replacement	Q_1, Q_2, Q_3, Q_4	CC_1, CC_2, CC_3, CC_4	$3R = \Sigma(Q_1 \times CC_1 + Q_2 \times CC_2 + Q_3 \times CC_3 + Q_4 \times CC_4)$	 Radar chart
	Cleaning	CA: cleaning area (m2)	CR: cleaning rate y: the setting of lifespan at the maintenance stage	$Cln = CR \times CA \times y$	
	Grounds maintenance	GMA: grounds maintenance area (m2)	GMR: grounds maintenance rate y: the setting of lifespan at the maintenance stage	$GM = GMR \times GMA \times y$	
	Redecoration	Q_1, Q_2, Q_3, Q_4	CC_1, CC_2, CC_3, CC_4	$Rd = \Sigma(Q_1 \times CC_1 + Q_2 \times CC_2 + Q_3 \times CC_3 + Q_4 \times CC_4)$	
	Tax	–	TR_i: tax rate on different classification	$TR_i \times (MM + 3R + Cln + GM + Rd)$	
End-of-life	Disposal inspection	FA: floor area (m2)	DIR_i: final condition inspection rate.	$DI = DIR_i \times FA$	 3D color chart
	Demolition of asset	Q_1, Q_2, Q_3, Q_4	CC_1, CC_2, CC_3, CC_4	$DA = \Sigma(Q1\times CC1 + Q2 \times CC2 + Q3 \times CC3+ Q4 \times CC4)$	
	Tax	–	TRi: tax rate on different classification	$TRi \times (DI + DA)$	

Table 4. Methods of data exchange for calculating LCC based on BIM

No.	Data exchange procedure	Graphic symbol	Advantage	Disadvantage	Example
(1)	From BIM to spreadsheet		1. Clear and transparent calculation process 2. Convenience by adopting existing software	1. Interoperability and compatibility issues 2. Slow and error-prone manual calculations	From Autodesk Revit to Microsoft Excel From Autodesk Revit to Microsoft Access From Autodesk Revit to SPSS From Graphisoft ArchiCAD to Microsoft Excel
(2)	From BIM to external software		1. Decrease in manual activity 2. Integration of different BIM models 3. Quickly edit information and update data	1. Interoperability and compatibility issues 2. Considerable investment of money and time by software developers	From Autodesk Revit to external software by authors From Autodesk Revit to Rhino From Autodesk Revit to Web Form BIM to IFC viewer From BIM to Edificius program by ACCA software From Graphisoft ArchiCAD to Legep From Graphisoft ArchiCAD to Vico Office
(3)	Including information in the BIM environment		1. Decrease in manual activity 2. Visualized result 3. Quickly edit information and update data	1. Considerable investment of money and time by software developers	Secondary development in Dynamo of Autodesk Revit Visual programming in Dynamo of Autodesk Revit

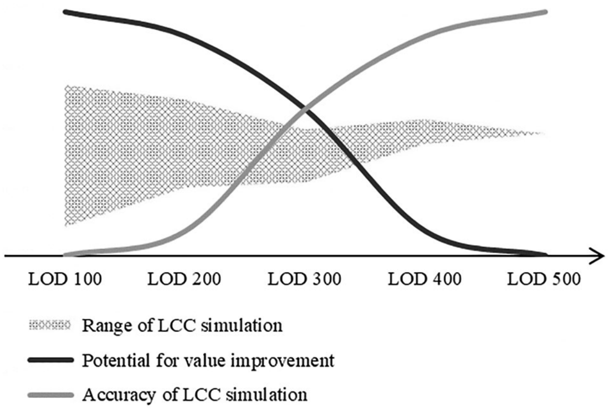


Figure 7. LCC simulation under dynamic LOD of BIM

4.2.2. Optimization measure

It is critical to use optimization measures to achieve value for money by reducing the LCC and improving the function of buildings. There are some option variables impacting the buildings' LCC result, including façade types (Liu et al., 2015; Ansah et al., 2020), window-to-wall ratio (Phillips et al., 2020; Liu et al., 2015), structural systems (AbouHamad & Abu-Hamd, 2019; Raposo et al., 2019), glazing types (Liu et al., 2015), and building orientation (Liu et al., 2015). Through BIM, designers can quickly get the results of LCC under different schemes and then choose the optimal scheme (Ahmad & Thaheem, 2018). The choice of scheme is especially important for green buildings (Marzouk et al., 2016, 2018; AbouHamad & Abu-Hamd, 2019), low-income buildings (Marzouk et al., 2016; Bianchi et al., 2021), and open buildings (Juan & Hsing, 2017) in value engineering.

4.2.3. Parameter analysis

The parameters of LCCA may be based on the wrong assumptions of owners or technicians, which is a big influence and affects the reliability of value engineering (Rodrigues et al., 2018). Therefore, LCC results need uncertainty and sensitivity analysis, which considers the uncertainty and sensitivity from the database, risk, and parameter settings. In the uncertainty analysis of LCC, Monte Carlo simulation is the most common method (Marzouk et al., 2018; Abouhamad & Abu-Hamd, 2019), while the fuzzy sets, Bayesian approach, and others can be possible choices (Marzouk & Abdelakder, 2020). In addition, the sensitivity analysis of life span or discount rate helps decision makers understand the economic value of time (Liu et al., 2015; Shin & Cho, 2015; Phillips et al., 2020). BIM can quickly update the results of LCC for value engineering, which provides a quick tool for parameter analysis.

4.3. Integration with other indicators

Some studies focused on weighing cost against other indicators. Ahmad and Thaheem (2018) not only considered LCC but also included affordability, manageability, and adaptability in the economic sustainability assessment. As shown in the Appendix, many studies integrated LCC and LCA to balance buildings' economic and environmental impacts. Additionally, some studies incorporated social impacts to achieve a triple-bottom-line (economy, environment, and society) assessment. By summarizing these studies, a methodological framework integrating LCC with other indicators based on BIM is presented in Figure 8, consisting of four steps framework following ISO 14040 and ISO 14044 (ISO, 2006a, 2006b): 1) Goal identification; 2) Inventory analysis; 3) Impact assessment; and 4) Interpretation.

4.3.1. Goal identification

In this step, construction categories, life cycle boundaries, accounting units, and other assumptions should be identified according to the customer's needs. Different construction categories, such as structure, envelope, interior, and equipment, are not always available under design processes (Cavalliere et al., 2019), which results in different boundaries. Also, the life cycle boundary and accounting unit are drawn on users' own merits. Another vital identification involves sustainable factors. LCC is not the only indicator for economic sustainability assessment but also affordability, manageability, and adaptability (Ahmad & Thaheem, 2018). When it comes to environmental assessment, some studies consider the trade-off between LCC and signal environmental impact, such as life cycle carbon emissions (LCCE) (Liu et al., 2015; Shin & Cho, 2015; Kim & Park, 2018) or life cycle energy (LCE) (Sandberg et al., 2019; Pučko et al., 2020; Kharazi et al., 2020). Furthermore, other studies cover multiple environmental impact indicators, including eutrophication potential (EP), acidification potential (AP), Smog Formation Potential (SFP), abiotic depletion potential of materials (ADPM), ozone depletion potential (ODP), photochemical ozone creation potential (POCP) and so on (Ansah et al., 2020; Yung & Wang, 2014; Phillips et al., 2020; Santos et al., 2019, 2020a, 2020b; Marzouk & Abdelakder, 2020). For social life cycle assessment (S-LCA), employment opportunities, building spaces (Yung & Wang, 2014) and daylight illuminance, glare index, and percentage of people dissatisfied (Phillips et al., 2020) should be involved in S-LCA.

4.3.2. Inventory analysis

The goal and system boundary above guide the establishment of the BIM model, including data standard, process standard, dictionary library standard, process translation standard, precision standard, and classification standard. The BIM model created by these criteria can export life cycle inventory (as shown in the column "Provided by BIM" of Table 3). Additionally, external databases need to be established. An economic example of that is the "Provided by designers" column in Table 3, and the environmental and social cases can be found in Martínez-Rocamora et al. (2016) and Çelik et al. (2017), respectively.

4.3.3. Impact assessment

After these economic, environmental, and social impacts are obtained for each part, these data are assembled. The analytic hierarchy process (AHP) (Bianchi et al., 2021; Jalilzadehazhari et al., 2019), Genetic Algorithm (Zhuang et al., 2021), NSGA-II genetic algorithm (Marzouk et al., 2016), Entropy-TOPSIS (Jalaei et al., 2015) can be used to balance these impacts. In addition, if environmental and social impacts can be monetized, these economic, environmental, and social costs can be summarized to get life cycle sustainability cost (LCSC).

4.3.4. Interpretation

The result needs to be analyzed and optimized to select the favorite option. The analysis plate includes sensitivity analysis, risk analysis, feasibility analysis, etc. Visual outputs should represent these results and analysis for the convenience of readers' understanding (seen in "Visualization types" in Table 3). Next, users can reassess proposed potential optimization options to the BIM model and obtain new results for choosing their favorite strategy. Additionally, the effect of the accuracy of BIM models on LCC results can be updated by this step.

5. Gaps and future research

Although there are many benefits to conducting LCC using BIM, some research gaps impact the development of LCCA and BIM. This review, therefore, elaborates on each limitation in these research topics and suggests potential solutions for future research (seen in Table 5).

5.1. OpenBIM

There are interoperability issues with different BIM tools (Fu et al., 2007). The storage formats of different BIM software developers are different (such as the rvt. from Autodesk and dgn. from Bentley) (Wu et al., 2021), which results in the separation of different BIM models.

Table 5. Research gaps and potential solutions for future research

Research topic	Gap and barrier	Future research
Calculation and data process	Lack of Interoperability and interaction between software	OpenBIM
	Lack of access without precise and complete drawings	Artificial Intelligence
Value engineering	Lack of post-study phase in value engineering	Extended LOD and IoT
	Lack of recycling and reuse in the linear economy	Circular economy
Integration with other indicators	Lack of direct comparison of other indicators with LCC	Monetization of other indicators

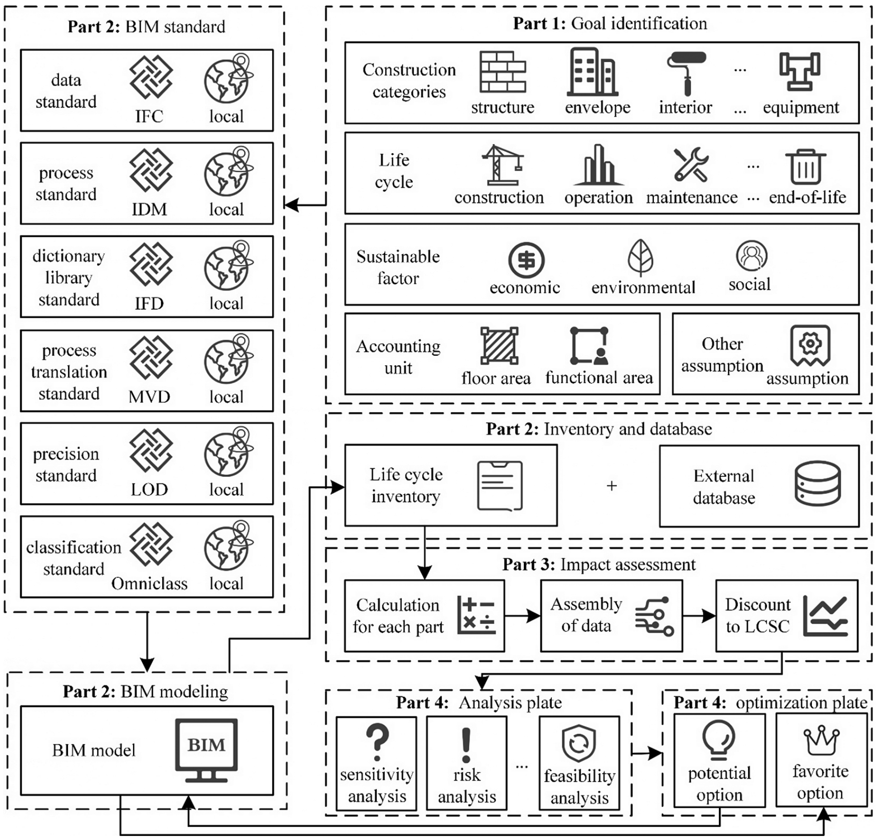


Figure 8. A methodological framework integrating LCC with other indicators based on BIM

Additionally, the model information from BIM cannot always be directly imported to LCCA software, which often needs manual input (Kehily & Underwood, 2017). In other words, existing BIM-based LCCA methods for buildings rely on specific software, and the information between this specific software cannot be transmitted and communicated.

OpenBIM, the concept with uniform data standards, maybe is the potential solution for this problem. It allows the LCCA to detach from specific software vendors. For example, IFC, the public BIM data storage standard, can be used to automatically calculate the bill of quantities (Choi et al., 2015) for embodied cost. Also, IFC can be used to simulate the operational energy consumption (Choi et al., 2016) for operation cost. In addition, IDM and MVD are also helpful for process translation to determine the LCC information carried by BIM models (Santos et al., 2019).

5.2. Artificial intelligence

Without precise and complete drawings, existing BIM-based LCCA methods are unavailable (Khodabakhshian & Toosi, 2021). Especially in the case of as-built old buildings, existing methods cannot perform LCC. It is possible to obtain BIM models of old buildings using 3D point cloud scanning (Rausch & Haas, 2021) and solve LCCA using existing BIM-based methods. However, 3D point cloud scanning costs are relatively large (Rausch & Haas, 2021), making it impossible to generalize this method. Moreover, this technology is still not suitable for problems without precise drawings in the conceptual design stage.

Artificial intelligence (AI) models, such as machine learning, convolutional neural networks, or artificial neural networks (Elmousalami, 2020), can provide a potential way to predict and evaluate LCC. BIM can feed data for LCC estimation using AI (Elmousalami, 2020), although the lack of real historical data on LCC collected from previous projects is still a major barrier in practice (Fu et al., 2007). Overall, owners or consultants can quickly predict the LCC performance of new or old buildings by accumulating historical LCC data using big data by BIM and a simulation model by AI.

5.3. Extended LOD and IoT

Current research mainly focuses on LCC simulation in the design phase, that is, the relatively early phase of value engineering (Jausovec & Sitar, 2019). However, value engineering involves the post-study phase, which is not currently involved but can be considered as a future research direction. For the BIM accuracy management, LOD500 can only be expressed until the as-built phase of buildings (AIA, 2007) and lacks expression for the subsequent stages. Although some studies have attempted to expand the LOD to the operation, maintenance, and end-of-life stage (Sadeghi et al., 2019), future studies still need to carry out LCCA under expanded LOD to meet the needs of post-evaluation for value engineering.

In addition, the Internet of Things (IoT) technology can dynamically collect a large amount of information generated in the life cycle of buildings in real time (Tang et al., 2019) and realize the real-time collection and summary of LCC. Furthermore, the real LCC data from IoT can be compared with the simulated LCC results from BIM to detect the implementation of LCCA, which is beneficial for the audit of LCC and the post-evaluation of value engineering.

5.4. Circular economy

The BIM-based LCCA patterns in existing studies are almost all linear economy. In these studies, the resources from construction, operation, and demolition are linearly aggregated to obtain the LCC results. In fact, many building components and resources still have residual value after the end of the service period of buildings (Akhimien et al., 2021). If the economic impact brought by the recycling of components is considered, economic sustainability can be achieved.

The circular economy concept requires the highest possible use of building components and resources to keep building components in a continuous loop of use, reuse, repair, and recycled (Akhimien et al., 2021). Jansen et al. (2020) established the theorical model for integrating LCC and circular economy. Also, BIM can record the information of components and resources, which is helpful for LCCA under the circular economy in future research.

5.5. Monetization of other indicators

More and more researchers have tried to combine environmental and social impacts with LCC to achieve LCSA, and the analytic hierarchy process (AHP) can be used to aggregate economic, social, and environmental impacts into a score for decision-making (Bianchi et al., 2021; Jalilzadehazhari et al., 2019). However, the scores of environmental and social indicators are often subjective and cannot be directly compared with economic costs.

Therefore, it is crucial to monetizing environmental and social impacts. Schneider-Marin and Lang (2020) developed a method to translate ecological indicators (such as carbon emissions) into environmental costs. As well as Çelik et al. (2017) quantified social indicators (such as noise) into social costs, which can be directly compared and optimized with economic costs. In addition, BIM also plays an active and useful role in helping calculate and assess social and environmental impacts (Llatas et al., 2020). Overall, based on BIM, the aggregation of economic, environmental, and social costs to form the life cycle sustainable cost is the goal of future research.

Conclusions

Through systematic literature, selection, and assessment, this paper has reviewed 45 studies to illustrate the ambiguous status quo of BIM-based LCCA caused by the absence of systematic review papers. The results show that the annual publications on this topic are increasing continuously. Case studies considering the value of time with 50 years are popular to verify research methodology. Although these cases involve various building types, research on hospital buildings and agricultural buildings is still lacking. At present, some mature commercial software can calculate the construction, maintenance, and demolition costs, and there is BEM software to simulate operational energy costs. However, mature LCCA commercial software based on BIM is still scarce.

The existing methods can carry out BIM-based LCCA evaluation through three data processing steps (data input, data calculation, data output) and three main data exchange processes (from BIM to spreadsheet, from BIM to external software, including information in the BIM environment). LCCA is not to reduce costs blindly but to achieve value for money. BIM can achieve accurate control of LCC through LOD, as well as optimization and parameter analysis. In general, low LOD is crucial for LCC control, although it cannot provide accurate LCC simulation results and vice versa. In order to achieve the LCSA for buildings, a methodological framework is summarized that combines LCC with other indicators to consider economic, environmental, and social impacts, which can be monetized to assess life cycle sustainability costs.

Six advantages are beneficial for LCCA based on BIM, including quickly predicting results, reducing unnecessary costs, quickly updating, visualizing results, transparently verifiable process, and collaborative work. However, there are still some barriers to integrating LCCA and BIM, which could be the future research directions: OpenBIM (IFC, IDM, MVD, IFD) harmonizes BIM standards and may be able to solve the lack of interactivity and compatibility between software. 3D point cloud scanning enables the rapid creation of BIM models for LCCA, while AI provides a predictive method based on previous LCC data provided by BIM models for the conceptual design phase without detailed drawings. The conjunction of Extended LOD and IoT is a potential means of conducting post-LCCA evaluations of value engineering. The circular economy concept should be introduced to recycle components and resources of buildings for linear LCCA-BIM patterns. Finally, environmental and social impacts should be monetized to directly compare and optimize economic costs, and BIM can help implement this process.

The main limitation of this study is the limited number of 45 papers, which is due to the professionalism of the topic, as well as only peer-reviewed journal papers being covered. Furthermore, although Scopus and Web of Science already cover the vast majority of high-quality papers, it is possible to elevate the uncertainty of the collected results.

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Author contributions

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Disclosure statement

The authors report there are no competing interests to declare.

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APPENDIX

Table A1. Summary information of existing research on LCCA based-on BIM

Reference	Net present value	BIM and its relative software	Data exchange process	Research focus	Additional analysis	Case study
Fu et al. (2007)	NPV: Discount rate (0.025%)	BIM: CAD system (AutoDesk Architecture Desktop)	Method 2: From Autodesk Architecture Desktop to IFC viewer Exchange format: IFC Database: Microsoft Access	IFC-based prototype tool to address not-compatible transported data	–	A building with 70 years
Yung and Wang (2014)	NPV: Interest rate	BIM: CAD system BEM: TRNSYS, EnergyPlus	Method 1: From CAD system to Microsoft Excel	Life cycle sustainability assessment (economic, environmental, social)	Environmental assessment, social assessment	Framework (without case study)
Liu et al. (2015)	NPV: Discount rate	BIM: Autodesk Revit BEM: Ecotect	Method 1: From Autodesk Revit to Microsoft Excel	Optimization LCC with life cycle carbon emissions using particle swarm optimization algorithm	Environmental assessment Optimization: particle swarm optimization algorithm	A ten floors office building with 50 years in Hong Kong
Jalaei et al. (2015)	NPV: discount rate, inflation, or deflation rate	BIM: Autodesk Revit BEM: Autodesk Green Building Studio	Method 1: From Autodesk Revit to SPSS and Microsoft Excel, Method 3: develop new plug-ins within the BIM tool using C# Exchange format: API	Decision support system by multiple criteria decision to optimize the selection of sustainable building components	Environmental Criteria, Economic factor, Social wellbeing	An actual five-floor office building in Ottawa, Canada
Shin and Cho (2015)	NPV: Discount rate	BIM: Graphisoft ArchiCAD BEM: EcoDesigner	Method 1: From Graphisoft ArchiCAD to Microsoft Excel	Select appropriate design alternative with consideration of LCA and LCCA	Environmental assessment (carbon emission), Sensitivity analysis	An 11-story office building with 40 years in the Republic of Korea
Marzouk et al. (2016)	NPV: discount rate (5%)	BIM: Autodesk Revit	Method 2: From Autodesk Revit to external software using C#	Sustainable low-income housing projects	Environmental aspects Green building certification: LEED Optimization: NSGA-II genetic algorithm	Low-income housing projects with 50 years in Badr City-Egypt
Kehily and Underwood (2017)	NPV: Discount rate (0.059)	BIM: Autodesk Revit Cost software: CostX	Method 2: From Autodesk Revit to external software	Embedding LCC in 5D BIM	–	A building with 30 years
Juan and Hsing (2017)	NPV: Discount rate	BIM: Autodesk Revit ventilation software: Vasari, Stream Daylighting software: Ecotect, Radiance Evacuation time software: Fire Dynamics Simulator LOD 200	Method 1: From Autodesk Revit to Microsoft Excel	Simulate building adaptive performance and LCC for an open building design	–	An Open Building with 30, 50, 100 years

Continue of Table A1

Reference	Net present value	BIM and its relative software	Data exchange process	Research focus	Additional analysis	Case study
Ahmad and Thaheem (2018)	NPV: Interest rate (0.0418, 0.0746)	BIM: Autodesk Revit	Method 1: From Autodesk Revit to Microsoft Excel	Economic sustainability assessment	Economic assessment: Affordability, manageability, adaptability	Three (standard, ideal, and subject) buildings with 40 years in Pakistan
Rodrigues et al. (2018)	NPV: discount rate	BIM: Autodesk Revit	Method 1: From Autodesk Revit to Microsoft Excel	Refurbishment of a traditional building	–	A building for 50 years in Oporto, Portugal
Marzouk et al. (2018)	NPV: Discount rate (10%)	BIM: Autodesk Revit	Method 2: From Autodesk Revit to external software	Optimizing LCC of sustainable buildings	Environmental impact Green building certification: LEED criteria, Optimization: NSGA-2 Uncertainty analysis: Monte Carlo Sensitivity analysis	A university with 80 years in Saudi Arabia
Kim and Park (2018)	NPV: Discount rate (0.78%)	BIM: Autodesk Revit BEM: IES VE	Method 1: From Autodesk Revit to Microsoft Excel	Delivering value for money for housing refurbishment	Environmental assessment: CO2 emission Value for money	A 2-story detached house with 60 years in the United Kingdom
Usman et al. (2018)	SPW	BIM: Autodesk Revit	Method 1: From Autodesk Revit to Microsoft Excel	Value engineering for optimization of renovation works	Value for money	A student center with 30 years
Vitiello et al. (2019)	NPV: Discount rate	BIM: general software	Method 2: From BIM to Edificius program created by ACCA software	Cost-optimization of seismic retrofit strategies on existing buildings considering seismic risk	–	An academic building in Naples Italian, built in the 1970s with no seismic provision
Sandberg et al. (2019)	NPV: Interest rate	BIM: Autodesk Revit, Graphisoft ArchiCAD	Method 2: From Autodesk Revit to Rhino using Grasshopper	Optimization of life-cycle energy and cost	Environmental assessment: Life cycle energy	A multifamily residential building distributed into five and six floors with 50 years in Sweden
Santos et al. (2019)	NPV: Discount rate	BIM: Autodesk Revit	Method 3: Secondary development using Dynamo of Autodesk Revit Exchange format: IFC, IDM, MVD	A tool using IFC schema to develop IDM/MVD for Integration of LCA and LCC	Environmental assessment:	A single-family house with 60 years in Belgium
Saridaki et al. (2019)	NPV: inflation and discount rate	BIM: Autodesk Revit	Method 1: From Autodesk Revit to Microsoft Excel Method 3: Visual programming using Dynamo	Data integration between design models and cost calculations	–	Three test cases: a simplistic design model, a university building model and a private company's office building model

Continue of Table A1

Reference	Net present value	BIM and its relative software	Data exchange process	Research focus	Additional analysis	Case study
Jalilzade-hazhari et al. (2019)	NPV: inflation rate (1%), discount rate (3%)	BIM: Autodesk Revit BEM: Design Builder- Energy Plus	Method 1: From Autodesk Revit to Microsoft Excel	Achieving a trade-off construction solution	Environmental assessment: Energy consumption Social assessment: Visual comfort, Thermal comfort	A 30 years office building located in climate Zone III in Gothenburg, Sweden
Zanni et al. (2019)	NPV: discount rate	BIM: Autodesk Revit, BEM: Designbuilder, IES LOD: Level 2	Method 1: From Autodesk Revit to Microsoft Excel Method 3: Secondary development using Dynamo of Autodesk Revit Exchange format: IFC, COBie	Integration of whole life costs into BIM processes	Environmental assessment: carbon dioxide equivalent	A Build-to-Rent building over a 15-year period
Jausovec and Sitar (2019)	NPV: inflation rate (construction cost 2%, energy price 4%, long-term 2% to 3%) default interest rates (2%), capital interest (5.5%), real interest rate (3.5%)	BIM: Graphisoft ArchiCAD BEM: EcoDesigner	Method 2: From Graphisoft ArchiCAD to Legep	Cost-optimal evaluation of prefabricated lightweight system envelopes	Value for Money	A two-story single-family house with 50 years in Slovenia
Abou-Hamad and Abu-Hamd (2019)	NPV: Discount rate (12.945%)	BIM: general software BEM: eQUEST	Method 1: From BIM to Microsoft Excel	Construction system selection based on LCC and sustainability assessment	Green building certification: LEED v4 Sensitivity analysis, Uncertainty analysis: Monte Carlo simulation	A 2-story university building with three different Structural systems with 50 years in Egypt
Raposo et al. (2019)	SPW	BIM: Autodesk Revit	Method 1: From Autodesk Revit to Microsoft Excel	BIM-based LCA assessment of seismic strengthening solutions	Environmental assessment	A single-story industrial building in Portugal
Fazeli et al. (2019)	SPW	BIM: Autodesk Revit, BEM: Green building studio	Method 1: From Autodesk Revit to Microsoft Excel Method 3: show results in the BIM tool	TOPSIS-Fuzzy framework to optimize the selection of sustainable building components	TOPSIS-Fuzzy	An office building in Vancouver, Canada
Marzouk and Abdelakder (2020)	SPW	BIM: Autodesk Revit	Method 1: From Autodesk Revit to Microsoft Excel or Microsoft Access	A hybrid fuzzy-optimization method	Environmental assessment Uncertainty analysis Optimization: genetic algorithm II	An educational building with 50 years in Saudi Arabia
Ansah et al. (2020)	SPW	BIM: Autodesk Revit BEM: IES VE	Method 1: From Autodesk Revit to Microsoft Excel	Different façade systems considering LCC and LCA	Environmental assessment	A single-story building with 50 years in Ghana
Santos et al. (2020b)	NPV: Discount rate (3%)	BIM: Autodesk Revit	Method 3: Secondary development using Dynamo of Autodesk Revit	Balancing LCA and LCC of an office building	Environment assessment	An office building with 50 years in the Netherlands

Continue of Table A1

Reference	Net present value	BIM and its relative software	Data exchange process	Research focus	Additional analysis	Case study
Lee et al. (2020)	NPV: Discount rate (0.72%)	BIM: Autodesk Revit LOD 100-200	Method 2: From Autodesk Revit to Web using Oracle SQL Developer to web	Preliminary estimation method for decision-making in the early design phase	–	Three projects with a similar use in South Korea
Le et al. (2020)	NPV: discount rate	BIM: Autodesk Revit LOD 300	Method 1: From Autodesk Revit to Microsoft Excel or Access Method 3: Secondary development using Dynamo of Autodesk Revit Exchange format: API	A BIM-integrated relational database management system for evaluating LCC	–	Academic buildings in Bangkok, Thailand
Santos et al. (2020a)	NPV: Discount rate (3%, 10%)	BIM: Autodesk Revit	Method 3: Secondary development using Dynamo of Autodesk Revit	Development of a BIM-based Environmental and Economic tool	Environment impact	A 250-m high tower with 50 years or 100 years in Morocco
Pučko et al. (2020)	NPV: discount rate (4%)	BIM: Graphisoft Archicad BEM: DesignBuilder	Method 2: From Graphisoft Archicad to Vico Office	Energy and cost analysis of building envelope components	Environment impact: energy	A two floors preschool building with 30 years
Phillips et al. (2020)	NPV: Interest rate (0%, 5%, 10%)	BIM: Autodesk Revit, BEM: EnergyPlus, occupant satisfaction: COMFEN	Method 1: From Autodesk Revit to Microsoft Excel	Triple bottom line sustainability assessment of the window-to-wall ratio	Environmental life cycle assessment Social assessment: Occupant satisfaction Sensitivity analysis	A large office building with 60 years in three climate zones in the USA
De Gaetani et al. (2020)	SPW	BIM: Autodesk Revit, BEM: Green Building Studio	Method 1: From Autodesk Revit to Microsoft Excel	Joint analysis of cost and energy savings for preliminary design	Environment impact: energy Investment Ratio $IR = \Delta C\ tot / \Delta EUI$	A realistic architectural project with 100 years of a single-family house in Milan or Livigno, in Lombardy, Italy
Yuan et al. (2020)	NPV: Interest rate	BEM: PKPM-Energy	Method 1: From Autodesk Revit to Microsoft Excel	BIM-VE-based optimization of the green building envelope	Value engineering	A residence building with 50 years in Nanjing, China
Kharazi et al. (2020)	NPV: discount rate 15%, inflation rate 9.5%	BIM: Autodesk Revit, BEM: Autodesk Green Building Studio LOD 300	Method 1: From Autodesk Revit to Microsoft Excel	Improving cost and energy performance of the building envelope	Environment impact: energy	A nine-story residential building with 30 years in Tehran, Iran
Matos et al. (2021)	SPW	BIM: Autodesk Revit	Method 1: From Autodesk Revit to Microsoft Excel Methods 3: visual categorization and color splasher using Dynamo	Building condition assessment	Building condition assessment	A school building with 50 years in Aveiro, Portugal

End of Table A1

Reference	Net present value	BIM and its relative software	Data exchange process	Research focus	Additional analysis	Case study
Rad et al. (2021)	NPV: discount rate (4.935%)	BIM: Autodesk Revit, BEM: green building studio	Method 1: From Autodesk Revit to Microsoft Access or Microsoft Excel Exchange format: API	Conduct LCCA of resilient buildings considering resiliency factors (earthquake) at the conceptual stage	–	A four-story residential building with two various types of structures in Victoria, Canada
Zhuang et al. (2021)	NPV: discount rate (6%)	BIM: Autodesk Revit BEM: EnergyPlus	Method 2: From Autodesk Revit to Rhino Database: MySQL	Performance data integrated for optimization design	Environment assessment: energy consumption Social assessment: indoor environmental quality	A green school building with 50 years in Nanjing, China
Bianchi et al. (2021)	SPW	BIM: Autodesk Revit	Method 1: From Autodesk Revit to Microsoft Excel	Alternatives for the design of sustainable low-income housing	Environmental impact, thermal comfort, construction time, and cultural acceptance	Buildings with three different structural systems in Brazil
Khoda-bakhshian and Toosi (2021)	NPV: discount rate (8%) Inflation rate (18%)	BIM: Autodesk Revit LOD 300	Method 1: From Autodesk Revit to Microsoft Excel	Residential real estate valuation	–	Two residential properties with 50 years in Tehran, Iran
Carvalho et al. (2021)	SPW	BIM: Autodesk Revit	Method 3: Secondary development using Dynamo of Autodesk Revit	Assessing environmental and economic impacts of building construction	Environmental life cycle assessment	18 different simulation scenarios with 50 years in Portugal
Soust-Verdaguer et al. (2021)	SPW	BIM: regardless of software	Method 3: Secondary development using Dynamo Exchange format: IFC	Life cycle sustainability assessment during design process	Environment assessment: CO_2 emission Social assessment: working hours	A residential building with 50 years in Seville, Spain
Al-Ghamdi and Al-Gahtani (2022)	NPV: inflation rate (3%)	BIM: Autodesk Revit	Method 3: Secondary development using Dynamo	Value Engineering for HVAC System	Value Engineering Analytical Hierarchy Process (AHP), Monte Carlo	An office building with 30 years in Saudi
Motalebi et al. (2022)	NPV: interest rate above inflation (2–3%)	BIM: Autodesk Revit BEM: Green Building Studio	Method 1: From Autodesk Revit to Microsoft Excel	LCA integration for energy efficiency retrofit	Environment impact	A multi-story residential building with 50 years in Tehran, Iran
Tushar et al. (2022)	NPV: discount rate (7%)	BIM: Autodesk Revit BEM: FirstRate5	Method 1: From Autodesk Revit to Microsoft Excel	Energy simulation for window system integrated LCA and LCC	Environment assessment: energy consumption	Window system with 60 years in Australia
Llatas et al. (2022)	SPW	BIM: Autodesk Revit LOD 200	Method 3: Secondary development using Dynamo Exchange format: IFC	Life cycle sustainability assessment in early design stages	Environment assessment: CO_2 emission Social assessment: working hours	A multi-family house with 50 years located in Seville, Spain