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Exploring the synergies between Life Cycle cost / Whole Life Cost and Building Information Modeling: A Systematic Literature Review

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Abstract. Life Cycle Costing (LCC) is a cost estimating approach for project and asset planning and delivery that considers the direct and indirect costs incurred over the entire life cycle of an asset. This approach can be expanded to the concept of Whole Life Cost (WLC), which additionally considers externalities and benefits. WLC can demonstrate the financial impacts, both positive and negative, of a project on its environment, in other words it can show its complete value. Despite its potential, the approach is still perceived as complex because, among other things, access to data can be difficult and the approach is still not supported by a standardized methodology. Building Information Modeling (BIM) could be used to address these issues as both WLC and BIM are deemed complementary. BIM provides WLC with better data management, improved calculation accuracy and visualization of project impacts. In return, WLC improves project understanding, decision making and reinforces life cycle thinking. This paper aims to study the potential synergies between BIM and WLC through a systematic literature review. The identification of these synergies helped form a frame of reference to better understand the opportunities that this combination can offer. Future studies would be needed to explore the application of BIM and WLC at different project scales and identify the context in which the combination of BIM and WLC is the most beneficial.

Introduction

Capital investments in construction are typically based on initial purchase cost. This focus on up-front costs hinders innovation, especially ecological innovations, whose higher investment cost is a major barrier to their implementation in projects. Thus, opportunities for both the project and the investor might be missed due to a lack of long-term investment and financing of projects and real property assets [1]. Nowadays, it is widely known that initial costs represent only a small proportion of the costs of a building, compared to the operating and end-of-life costs. It is also known that choices made in the early phases can have the most impact on the entire project [2–5]. In this context, Life Cycle Costing (LCC) appears as a relevant solution to ensure that the best choices are made to generate value for an asset. LCC is defined by ISO 15686-5 as the "*cost of an asset or its parts throughout its life cycle, while fulfilling the performance requirements*", and its function is to quantify life cycle costs to support decision making and evaluation processes. Thus, the LCC can not only help to estimate capital expenditures but also estimate and control future expenditures, a nuance that makes it possible to find the best compromises to optimize the cost of a project asset across its entire life cycle [6]. The estimation can be made more complete and more accurate with a Whole Life Costing (WLC) approach, introduced by ISO 15686-5 as *"all significant and relevant initial and future costs and benefits of an asset, throughout its life cycle, while fulfilling the performance requirements"*. In other words, WLC includes LCC, benefits, non-construction costs and externalities that can be quantified and expressed in monetary terms (e.g., carbon emissions) [7]. Owners may benefit from WLC to design projects that align with their organization's capacity to afford facility costs relating to maintenance but also to minimize environmental impacts [8]. Even though WLC shows great potential, certain barriers are limiting its widespread adoption, such as, the difficulty to access data and its complexity and lack of methodology [9]. Recent studies have shown that BIM could help facilitate the application of WLC and overcome these barriers. However, these studies are mostly focused on practical ways to combine WLC and BIM and actual literature as to theoretical bases is still lacking. This paper aims to study the application of BIM and WLC using a systematic literature review based on this research question: What synergies do BIM and WLC share? After identifying these, we followed the methodology developed by Jabareen [10] and created a conceptual framework. This reference framework could help to better understand the opportunities resulting from the application of both approaches for future studies.

Literature Review

Life cycle thinking can potentially offer real control over projects and guarantee best value for real property assets and asset portfolios. Each choice made, especially in the early lifecycle phases, will have an impact on the whole life cycle of an asset. Indeed, Mistry [11] used LCC and Life cycle analysis (LCA) as indicators to assess the performance of a pier. It was shown that the modification of just one material had significant environmental and economic impacts on the asset's life cycle. Therefore, if an optimal result is to be achieved, it is important to consider an asset as a whole. To reiterate, ISO 15685-5 defines the main role of LCC as the quantification of life cycle costs to support decision-making and evaluation processes throughout the entire project. Because WLC enables the financial analysis of externalities, associating it with other concepts offers great opportunities to improve project quality by offering a financial point-of-view. Indeed, WLC can help in waste management [12], Circular Economy [13], Value for money [14] and Target Costing [15]. It also has been demonstrated that WLC is a powerful tool for negotiations and can have a positive impact on project communication if used collaboratively [16]. Despite its utility, WLC still faces barriers and it is not widely used. Higham [17] studied the barriers of LCC in the UK construction industry and revealed that the major blockage lies in the client's habit of short-term budgeting and in the lack of awareness of the benefits of the approach. Another issue reported in the literature was the subjectivity of the calculation parameters, especially for the discount rate, which has a significant impact on the forecasting process [18]. This implies the possibility of over- or under-estimating the calculation assumptions [19]. One of the main challenges resides in data collection and management. Indeed, collecting all the data needed for the estimation can be difficult and very time-consuming. Also, data may be inexistent or inaccessible if there is no life cycle inventory available for the project [20]. Applying BIM for WLC is a new recent trend in the literature and it appears to be overcoming some of the barriers mentioned here. Indeed, BIM is seen to have the capability to automate the process of WLC and to be used as a data repository [21]. Past research has also looked at specific applications of BIM for WLC. Lu [22] conducted a systematic literature review (SLR) focusing on practical approaches to implement BIM for WLC. He proposed a framework describing how to integrate BIM by linking a spreadsheet, using an external platform, or directly using the BIM modeling environment. To demonstrate that BIM can enhance LCC, Altaf [23] conducted an SLR that aimed to identify the potential for BIM in automating the LCC approach. The study resulted in a framework to calculate LCC with BIM. Moreover, while the study proposed a theoretical basis for BIM and LCC, only one database was explored. Thus, there seems to be a lack of research investigating the current trends, barriers and opportunities of BIM for WLC. The research presented in this paper addresses this gap.

Research Methodology

In this paper, a systematic literature review (SLR) was undertaken to identify the synergies between BIM and WLC. The SLR was performed using the following terms: ("Building Information Modelling" OR "BIM") AND ("Life Cycle Cost" OR "Whole Life Cost" OR "LCC" OR "WLC") inside the following databases: Scopus, ASCE, Compendex, Emerald Insight, IEE explore, Science Direct, Web of Science. For this study, peer-reviewed research articles, but also grey literature like technical reports, theses and dissertations, conference papers, committee reports, and government documents were used. Grey literature was also included and searched for in the following databases: ProQuest, Open Access Theses and Dissertations (OATD) and GLOBAL ETD. The results were limited to studies related to the application of BIM and WLC at the project scale in the construction sector. Only studies in English and French were selected. No time or location limits were set. Once the strategy was established, a PRISMA flow chart of the SLR was followed (Figure 1). For the peer-reviewed documents, the key terms searched for in the mentioned databases allowed the research team to identify 1360 results that were imported into Zotero. Zotero is a reference management software that facilitates the collection and organization of references. Once duplicates were removed, a total of 932 documents remained. Each abstract was analyzed to exclude irrelevant studies, e.g., those not in English or French and those not related to the construction sector. To achieve this, excluding criteria were defined as follow: Language is not English or French, the study does not concern construction domain, the abstract does not mention a cost estimation or management of the project, the abstract does not mention that life cycle is considered, and the scope of the study does not consider the asset performance. Thus, studies about life cycle cost estimation or management of construction projects were kept for full assessment. The abstract screening process retained 119 documents, 110 of which could be retrieved and were fully assessed for eligibility. This step allowed to identify studies using BIM to conduct life cycle cost estimation or management. In the end, 81 studies were retained for the study. For grey literature, keywords had to be changed for Global ETD and OATD databases as these search engines are less elaborate, limiting the search respectively to "BIM" AND "Life cycle cost" and "BIM" OR Building information modelling" AND "Life cycle cost" OR "Whole life cost". A total of 161 documents were identified of which 80 duplicates were removed and 9 were not accessible. Therefore, 72 documents were identified for analysis. Among these, 4 were neither in English nor in French, 11 were not in the construction sector and 49 did not involve BIM or WLC in the study. In all, 8 grey literature documents were considered, for a total of 89 documents for this SLR. The documents were then analyzed by identifying the utility and expectations of BIM to the project, the utility and expectations of WLC with regards to the project, the BIM impacts on WLC, and WLC impacts on BIM.

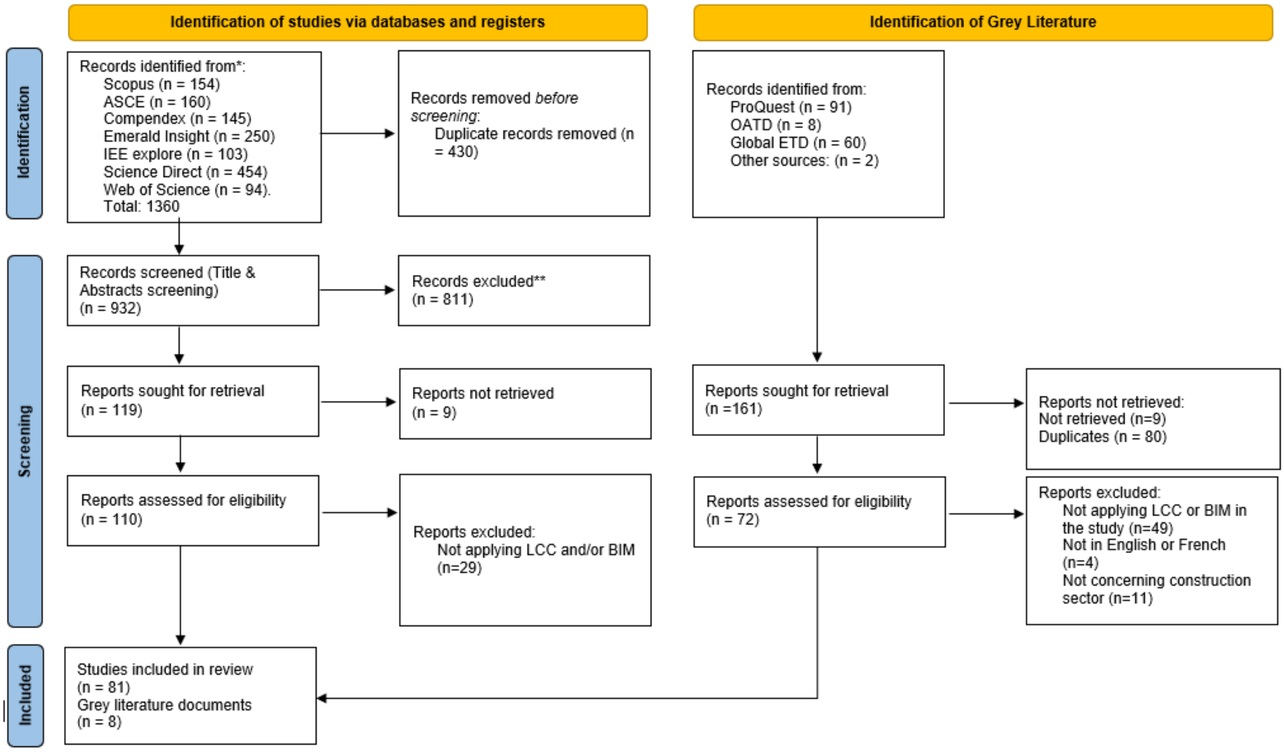

Figure 1: PRISMA flow chart

The SLR was complemented with a conceptual analysis, as proposed by Jabareen [10], to build a conceptual framework. Jabareen's methodology involves steps resembling the data collection process of the SLR, but it goes further with subsequent steps that identify and name each concept found in the studies, to define them, their attributes and their role and integrate them into a conceptual framework.

Findings and Discussion

In this section the results of the data analysis are presented. First, the interactions between BIM and WLC are investigated to determine their complementarities. Then, the concepts resulting from the use of BIM and WLC will be identified and deconstructed before being integrated into a reference framework.

4.1. Complementarities between BIM and WLC

The results of the interaction between BIM and WLC when used in a project are summarized in Table 1. The primary benefit of BIM is its potential to overcome the data accessibility barrier of WLC, that leads to time consuming quantification and cost estimation. In fact, BIM models have the potential to automate the approach thanks to their quantity take off (QTO) process and ability to integrate/be linked to a database. Some authors have worked on this, like Kehily [24], who demonstrated how the 5D BIM tool CostX, can be used to extract quantity to conduct LCC estimation, or Santos [21], who proposed to integrate LCC information directly inside the BIM model to automate the process. Moreover, easy simulation testing with BIM makes it possible to simulate alternative scenarios and see how WLC will affect the project. An example can be found in a study by Omaran [25] in which he linked a game engine to BIM, to visit the project virtually and make changes to it, to highlight the impacts of the alternatives on the project LCC. BIM also helps in conducting WLC for organizational aspects, as it facilitates collaboration and the managing of the huge amounts of data needed to conduct an WLC analysis [26]. In his study, Rodrigues [27] integrated shared parameters about maintenance, quantity, and costs into the BIM model to facilitate data management and prepare preventive maintenance plans. He supported his model with LCC to find best alternatives. Also, BIM reduces human errors and facilitates the use of WLC at early design stages for a more efficient approach application. Lee [28] used a BIM-based LCC preliminary estimation at an early design stage and showed that BIM provided more precise results even at the design stage. Finally, WLC can provide a new indicator, which, once integrated into a BIM model, is easily readable and shareable [29], reinforcing the decision-making process as it makes it possible to compare data on a financial basis.

Table 1: Complementarities between BIM and WLC

WLC advantages for a BIM project	BIM advantages for a WLC approach
Reinforces decision-making and project cost control Enriches BIM model Reinforces life cycle thinking	Provides automatic quantity take-off Can serve as a repository database Easy simulation Facilitates management of data Facilitates the use of WLC at early design stage Provides better quality data and reduces human errors, increases precision Provides easily readable and shareable results

4.2. Synergic use of BIM and WLC

BIM greatly supports and enhances WLC. Conversely, BIM can be improved and augmented through WLC. The combination of both can make it possible to apply interesting concepts that can enhance a project f. Based on the analysis of the data collected, it appears that the combination of BIM and WLC can contribute to the application of processes, concepts and methodologies. The latter are summarized in Table 2 and the next section will present how BIM and WLC facilitate their use. The process that is reinforced by the combination of BIM and WLC is decision making. This is the predominant topic in our research because supporting decision making is the purpose of WLC. Each study collected could have been identified in the DM line in Table 2, but only studies that focused on WLC are indicated for organizational purposes.

Concerning these concepts, a study from Di Biccari [29] investigated the use of BIM to support Circular Economy (CE) and LCC indicators to compare alternatives more easily, while Kim [30] proposed a design support tool for material reuse assessment, utilizing BIM to extract data from the deconstructed structure and LCC as an indicator of assessment. Another concept found was Net Zero Emission (NZE), referring to energy consumption and carbon reduction. Some studies worked on both and some on just one. Akbarnezhad [31] worked on both topics and evaluated disassembly techniques to find those best in terms of costs, energy consumption and carbon emissions. Of those who worked on just one of these topics, there is Kabassi [32], who used BIM to build an energy model and LCC model to compare sustainable design to assess the cost-effectiveness of a Zero Net Energy Test House, and Figl [33] who proposed a 6D BIM terminal to analyze projects through LCC and LCA to plan C02-neutral buildings. Energy and carbon were grouped because of the correlation between them. Another concept is value engineering, which merges the concepts of Value for money (VFM), value engineering (VE) and value management (VM). Jausovec [3] used LCC to conduct a VFM analysis and find cost-effective prefabricated systems for a building, using BIM as a data repository and evaluation tool for LCC. Usman [34] used the functionality of a 3D BIM model to facilitate the VE approach integrated with LCC. Punnyasoma [35] used BIM for QTO and cost evaluation, and LCC to find the highest cost-effective solution with lowest LCC for VM. The final concept found was construction and demolition waste management (CDWM) studied by Zoghi [36], reducing CDW costs using a BIM-based waste management system, and evaluating LCC effective solutions.

Regarding methodologies, Life Cycle Analysis (LCA) is a noticeable trend of study in the literature. In fact, LCA is presented as a complement to LCC and authors like Santos [37] proposed a BIM-LCA-LCC framework by integrating parametric data into a BIM model. BIM-based WLC is also used to leverage Life cycle management (LCM). LCM regroups studies on whole life management as seen in the study by Rodrigues [27] presented above, and studies on facility management as seen in a study by Vitiello [38], who used BIM as a database and LCC as an indicator to evaluate the cost effectiveness of retrofitting designs, considering economic loss expectations in a context of seismic risk. Still, in life cycle thinking, the following two approaches are similar: Life Cycle Sustainability Analysis (LCSA) and Triple Bottom Line (TBL). Both use LCC as an indicator and measure environmental and social factors in specific metrics to complete their analysis. Figueiredo [39] used LCSA to select materials, partly using LCC in the evaluation and BIM as a database to extract quantities and simulations. An example of TBL is presented in the study by Phillips [40], who used it to find the best window-to-wall ratio by conducting BIM-based LCA and LCC and measuring occupant satisfaction. Finally, Multi Objective Optimization (MOO) is another prevalent methodology in the literature. Sandberg [41] proposed an optimization model based on a master model, which can generate different domain models for evaluation and optimization, then the optimal solution is sent back to the master model. He used an energy model and life cycle costing model to find the optimal sustainable performance for a building.

Table 2: Identified concepts from the application of BIM and WLC

	Process	
Decision making (DM)	Process of choosing options and alternatives according to project expectations. Its main objective is to optimize the investments made to obtain expected performance.	[5,23–26,28,42–59]
	Concepts	
Circular Economy (CE)	Concept that has a closed-loop life cycle perspective of products instead of a linear life cycle perspective by utilizing restorative/regenerative designs. It is used to optimize the use of products/ materials to reduce waste generation.	[29–31]
Net Zero Emissions (NZE)	Concept used for the design of high energy efficiency buildings to reduce energy consumption and thus carbon emissions, to reduce the building's carbon footprint.	[2,4,32,33,60–69]
Value Engineering (VE)	Concept used to optimize decision making to create value through the life cycle of a project by considering costs, benefits and quality.	[3,34,35,70–73]
Waste management (WM)	Concept relating to the optimization and reduction of construction waste production, reuse, recycling and disposal.	[31,36]
	Methodologies	
Life cycle analysis (LCA)	Cradle-to-grave analysis to assess and quantify the environmental performance of a product or project. Used to collect and analyze environmental data to assess impacts.	[21,22,37,74–80]
Building Life cycle management (BLCM)	Data asset manipulation and exchange throughout a building's life cycle. It helps to manage the asset's performance throughout its life cycle and guarantee its serviceability.	[27,38,81–84]

Life cycle sustainability assessment (LCSA) and Triple Bottom Line (TBL)	MOO approaches based on the three pillars of sustainability (social, environmental, and economic) to optimize projects. Their objective is to analyze the durability of an asset through its environmental, economic and social performances.	[39,40,85,86]
Multi-Objective Optimization (MOO)	Methodology that aims to obtain the best trade-off between two or more expectations for a design or project. Its role is to analyze a product/project on multiple planes to highlight its specific performances.	[41,60,87–95]

Additionally, Table 3 presents Machine Learning (ML) and Genetic algorithm (GA). Both are emerging as a new trend to enhance WLC. Gao [55] proposed a ML-based framework to analyze the LCC of facilities. The framework uses a BIM model and design and construction documentation to collect descriptive data for the ML models with different methods of calculation. Then an evaluation phase provides the method and results for the project. Dawood [88] used a GA to combine multiple variable components and found the combination that best represents the optimal LCC of the project. He used a BIM model to serve as a database for the building components, find the quantities for initial cost estimation and perform an energy analysis.

Table 3: WLC facilitators

Facilitators		
Machine Learning (ML)	Develops predictions through the automatic evaluation of a set of data patterns	[55,94]
Genetic Algorithm (GA)	Optimization method based on the human chromosome model. Each chromosome represents a solution composed of several genes representing components of the solution.	[41,45,61,88,90]

4.3.Reference framework creation
Concepts previously defined are now integrated into the reference framework presented in Figure 2. The framework establishes the links between the combination of BIM and WLC, the different process, concepts, methodologies and facilitators. The BIM/WLC combination and in particular the application of WLC, can be facilitated by ML and GA. Then, WLC can leverage the methodologies identified, which can in turn help to implement the concepts of CE, NZE, VE and WM. Finally, the decision-making process is the basis of the hierarchical organization of the framework, as it is the underlying purpose of each of these elements. For the methodologies, WLC provides a financial perspective when assessing assets and BIM can serve as a data repository, facilitate data management and extraction and can be used to perform simulations. As for the concepts, WLC is used as an indicator for representations, facilitated through BIM.

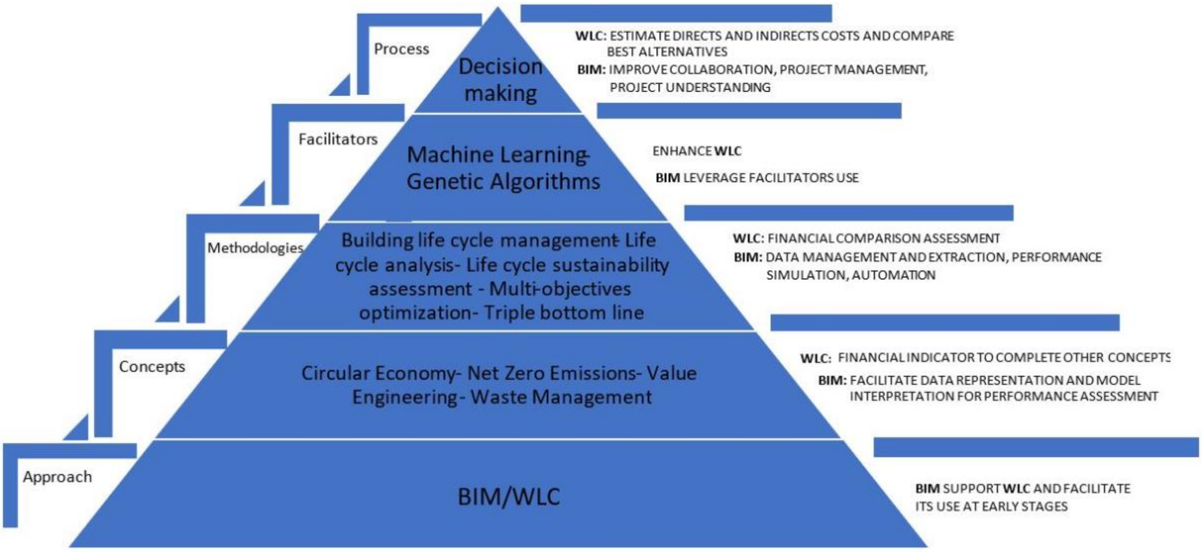

Figure 2: Frame of reference for the use of BIM-WLC combination

By comparing the WLC barriers described in the literature review and BIM-WLC complementarities and synergies, it appears that, considering an optimal combination of the two, major barriers of WLC could be overcome. Indeed, BIM can reduce the time and complexity of the process of WLC considerably and even automate it. It can help to manage data and encourage information sharing to conduct the estimation. One of the major opportunities that BIM can offer is its ability to store data and act as a database, satisfying the need for complete and easily accessible life cycle data. Easy simulation of BIM can help to generate alternatives and increase the precision of WLC results. In addition, the synergic use of BIM and WLC offers the opportunity to apply other concepts that could be more adequate and efficient or complementary to WLC, depending on the project. Moreover, the facilitators identified will greatly improve the methodologies for estimating operating costs. These methodologies are currently based on historical data from similar projects and the experience of estimators, especially for innovations, and it can be difficult to systematically estimate indirect costs over the life of the building. The easy use of these facilitators through BIM will improve the reliability of these methodologies and therefore of the WLC. Unfortunately, the application of an optimal BIM-based WLC approach is still faced with certain barriers. Indeed, there is still a lack of standardization in its methodology, data gathering remains a challenge and interoperability issues may prevent the use of BIM [54]. In addition, there are barriers to WLC that BIM cannot yet overcome. The concept of the approach is still complex despite BIM and it is recommended that the non-informed project stakeholders receive training [96]. considering the implementation, it appears that it still remains an obstacle and one of the main reasons seems to be that the literature does not present a clear identification of the end user of WLC. In other words, who in practice will benefit from the data generated from this approach, who will use it and how? WLC seems to be most often used in design to make sustainable choices, thus to give it more interest, a clear answer to these questions would allow the integration of the approach into the life cycle management process and could encourage its implementation. Also, confidence in WLC predictions still depends on the reliability of forecasting and the right choice of discount rate. In fact, even if BIM overcame some barriers, a great subjectivity would remain as to the choice of parameters, meaning that errors in forecasting could still occur and falsify the results.

Conclusions and Further Research

WLC is an appropriate method to assess investments that are beyond the initial costs of a project. The approach can be useful to control the direct and indirect costs of a project and produce value. A recent trend in the literature is to use both BIM and WLC to improve the cost estimation approach. The present research aimed to explore the synergies between BIM and WLC through a systematic literature review. It was found that BIM and WLC are complementary. BIM helps to overcome some of the barriers of WLC and WLC supports the life cycle thinking and collaborative nature of BIM. Moreover, their synergy makes it possible to use other concepts like circular economy or value engineering. The combination of BIM and WLC has a great potential to improve practices in the construction industry. The present paper also showed that BIM and WLC have a great potential to improve decision making in projects. Many studies also showed the benefits of WLC when leveraging it with environmentally-friendly and/or value producing concepts. Furthermore, current literature seems to be directed towards technological improvements such as interoperability, which is one of the main obstacles of BIM. More recently, the literature has mostly tended to optimize the BIM-WLC combination to fully take advantage of it, by leveraging facilitators like machine learning and genetic algorithms to enhance WLC results, and some authors relied on databases to fully overcome the data gathering barrier[23]. Further study should address the fundamental issue of the confidence in predictions by WLC and its parameters, because these are the principal reasons why long-term budgeting is not in the habit of owners and why the widespread adoption of WLC is hindered. Considering the implementation, an investigation should be made about the clear definition of the end user of the approach and the integration of the generated data into the asset life cycle management process. Finally, further studies should explore the application of BIM and WLC at different project scales and identify the context in which the combination of BIM and WLC is most beneficial. Concerning this work, more grey literature could and should be added to the study, but accessibility to grey literature is still a major barrier to its consideration. Industry actors generate a lot of quality data, and it could be interesting to investigate a significant amount of it to collect feedback on this subject from their experiences.

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