Process Map for Accessing Automatization of Life Cycle Assessment Utilizing Building Information Modeling

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Abstract: Despite the importance of life cycle assessment (LCA) in inspecting environmental impacts, its execution through manual methods affects the quality of the results, besides consuming the time and effort of decision-makers in the construction industry, such as designers, implementers, facility managers, and consultants. When LCA relies on building information modeling (BIM), it encounters many difficulties and obstacles, such as human intervention, conflicts among platforms and environmental databases, and no coordination to integrate or manage information. Thus, the research aims to support LCA through automatized integration with BIM depending on BIM's role in information management, promoting decisions, and activating BIM implementation success factors to make the BIM model qualified for the LCA. Then, the BIM and LCA overlap methods were analyzed and exemplified. Also, the requirements of their integration strategies were identified for LCA to become automated from now. Accordingly, the process map that supports and coordinates the automatized integration of LCA and BIM, overcomes integration difficulties, and conducts LCA through automated methods was deduced and structured. The analytical hierarchy process was applied through the survey using questionnaires and interviews to validate this map. The survey affirmed that the BIM model acquired new characteristics and will play an essential role in the LCA's accuracy, reliability, and comprehensiveness. This map supports the standardization and alternative strategies of the workflow. Furthermore, the interconnected stages of this map as a scenario can conduct an LCA within any project's life stage and guarantee its quality. **DOI: 10.1061/JAEIED.AEENG-1449**.

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Introduction

Despite the importance of life cycle assessment (LCA) and its role in improving the buildings' performance, many still do it manually, which may not fulfill the purpose of the LCA study and affect the accuracy of the results (Hollberg et al. 2021; Lützkendorf 2018). The LCA may not be able to perform some calculations related to environmental impacts or errors in entering information, such as energy analyses, human activity, and buildings' behavior, such as the assembly and construction materials (pre- and postoccupancy) have considered the embedded impact. Also, the building's energy usage is related to operational impact (occupancy stage) (Al-Ghamdi and Bilec 2017; Cavalliere et al. 2018; van der Giesen et al. 2020; Jalaei et al. 2019). Thus, LCA requires finding solutions to overcome these shortages through a technological intervention or platforms that preserve information and work on processing and familiarizing with it while performing calculations through incorporation, linkage, and integration with technologies such as building information modeling (BIM) (Jalaei and Jrade 2014). In addition, the role of BIM in making decisions and managing information through performed and tested solutions and alternatives on the model many times, whether for a new or an existing building; the idea is that BIM coordinates procedures and solution steps to provide methods, avenues, or information for conducting LCA analyses (Al-Ghamdi and Bilec 2017; Bishop et al. 2021; Lim 2017; Lu et al. 2017; Najjar et al. 2022; Nowak et al. 2016). Also, the construction industry is undergoing a significant digitalization process with the prompt for BIM use in all project stages. These allow for efficiently sharing the building information among specialists and stakeholders and reutilizing data during various stages (Wastiels and Decuypere 2019). Simultaneously, the increased worries about the environmental effects of buildings lead to a requirement for a complete LCA at all stages. Databases and tools of LCA are still in evolution, and it is unclear how to effectively adapt the requests of the LCA practitioners to those of the design team (Bueno and Fabricio 2018). As a result, it is still unclear how to effectively integrate the LCA study into the BIM-based design workflow in a world where most data transmission between BIM and LCA is done manually presently (Obrecht et al. 2020; Röck et al. 2018).

All this drives toward standing on and identifying the success factors of BIM implementation to support the LCA procedure to provide the required information and make the BIM model qualified to perform such analyses. Accordingly, integrating BIM with LCA can be automated; hence, manual methods and human intervention become minimal to reduce errors, save time and effort, and ensure that the LCA results are correct, accurate, and reliable. Besides, the LCA recalculation is easy to make at any stage of the project life, and the required adjustments are quick and easy (Al-Ghamdi and Bilec 2017; Cavalliere et al. 2018; van der Giesen et al. 2020). All the aforementioned will positively affect the financial aspects of the projects and increase the added value of any project that achieves this automatized integration. Accordingly, this requires inserting a methodical technique, approach, or implementation plan as a process map of the BIM-based LCA procedure and a path to its automated integration.

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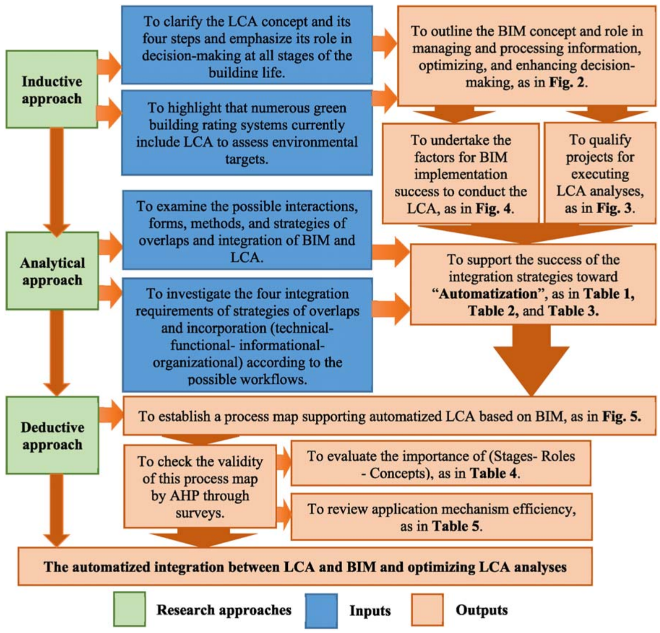

Fig. 1. Flowchart of the study methodology.

The BIM role for LCA (managing and processing data and optimizing and enhancing decision-making)	It has several platforms consistent with required LCA outcomes.
	It visualizes LCA incomes and outcomes.
	It assists in explaining and making decisions.
	It has criteria or standardized methods for presenting LCA results.
	It evaluates material and energy flows at all project life cycles.
	It gathers crucial information about LCA.
	It decreases the time and effort required for LCA analyses.
	It identifies and mitigates environmental hotspots.
	It determines the discrepancies in the results and provides guidance.
	It recalculates depending on the infinite modification possibilities within a model.

Fig. 2. Concept and role of BIM in managing and processing LCA information, besides optimizing and enhancing decision-making.

Research Problem

Manual methods have been used to perform LCA analysis and information exchange between LCA and BIM tools (Hollberg et al. 2021; Jalaei and Jrade 2014; Lützkendorf 2018). Therefore, this leaves gaps that cause errors or incomplete entry of the information required to perform LCA calculations, such as energy analysis and human activity. Also, building behavior is where the assembly and construction materials are an embedded impact, while the building's energy usage is an operational impact. Incorporating and overlapping LCA and BIM technologies faces many difficulties and obstacles hindering automatizing their integration (Antón and Díaz 2014; Cavka et al. 2017; Soust-Verdaguer et al. 2017; Volk et al. 2014). That is because there is no plan, guide, or tactic to achieve this automatized integration during conducting LCAs in a more accurate, quality, fast, and easy way. Besides, there is a need for dealing with different platforms, tools, and environmental databases and treating conflicts between them in all stages of LCA analyses (Mohammed 2022; Obrecht et al. 2020; Raouf and Al-Ghamdi 2019).

Research Aims and Objectives

The study aims to automatize LCA based on BIM by inferring and establishing a process map to optimize executing and conducting

The qualification actions of projects for executing LCA	Coordinate and harmonize policies, processes, and technologies.
	Provide geometric or non-geometric properties on parametric objects with semantic, functional, or topology information.
	Comprise data on the quantity and quality of materials of embodied environmental consequences.
	Incorporate supplemental data on environmental impacts and other LCA study inputs.
	Assist in the most accurate and timely data exchange and suitability among stakeholders.
	Contribute to the LCA's significant value during the later modeling stages.
	Increase the data traffic quantity and the value of platforms for managing such data.

Fig. 3. Qualification actions of projects for executing LCA analyses.

The factors of BIM implementation success for conducting LCA	Collaboration among stakeholders in the design, planning, and construction
	Earlier and more precise 3D visualization of proposals
	Coordination and planning of building activities
	Data exchange enhancement and information management
	Enhanced site layout planning and site safety

Fig. 4. Factors for the BIM implementation success during utilizing BIM to conduct LCA.

LCA analyses because of the efficiency and influential role of BIM in managing information, making decisions, and simulating all stages of a project; hence, LCA becomes more comprehensive, accurate, and reliable. The objectives of this study are as follows:

1. To activate and root the role of BIM in processing data, enhancing decision-making, and BIM implementation success factors that will support LCA execution and make a BIM model qualified for conducting the LCA;
2. To identify and investigate the methods and strategies of integration and overlap between BIM and LCA as well as the integration requirements that support the success of this integration in an automated manner; and
3. To derive and structure the process map that supports the automatized integration of LCA and BIM and overcomes difficulties of integration and LCA implementation and then check the validity of this process map.

Research Methodology

Inductive Approach

The study depended on the inductive approach to clarify, explain the LCA concept and the four LCA steps, and emphasize its role in decision-making at all stages of the building life. Moreover, many green building rating systems currently use LCA to assess environmental targets, highlighting their need for technological tools to enhance data management and simulate LCA results as BIM. The outputs of this approach were, as shown in Fig. 2, the concept and role of BIM outlined and indicated in managing and processing information, besides optimizing and enhancing decision-making. Hence, avoiding the failure of BIM-based projects and making them qualified by the actions, as shown in Fig. 3, for executing LCA analyses. Consequently, the factors for the success of BIM implementation, as shown in Fig. 4, were collected and identified to be undertaken while handling BIM to conduct the LCA.

Analytical Approach

The study used the analytical approach to appraise and investigate the possible interactions, forms, methods, and strategies of overlap and integration of BIM and LCA tools, programs, and platforms by analyzing specific previous studies. In addition, the study inferred, analyzed, and examined the four integration requirements of the strategies of overlaps and incorporation (technical–functional–informational–organizational). Accordingly, the approach outputs support the success of the integration strategies according to the possible workflows, as given in Tables 1–3, to attain their potential automatization.

Deductive Approach

Based on the two previous approaches, as shown in Fig. 1, the study employed the deductive approach to derive and formulate a process map supporting automatized LCA based on BIM to conduct the LCA through three stages (preparation and equipment, modeling and qualification, and LCA analysis) as a final result, as shown in Fig. 5. Hence, the study clarified the concept and role of the process map to solve all integration difficulties. Also, the results of the calculated environmental impacts are more accurate and reliable. The validity of this process map was evaluated, as given in Tables 4 and 5, via the analytical hierarchy process (AHP) through surveying to assess the importance of its stages and application mechanism efficiency for achieving the automatized integration, enhancing, and optimizing LCA analyses. Fifty experts and practitioners in the sustainability, LCA, and BIM fields performed two rounds of questionnaires and interviews.

Life Cycle Assessment

Promoting long-term sustainable development depends on significantly mitigating the environmental impacts of the building industry. LCA is a well-established methodology for quantifying the consequences of the environment. Its use is increasingly to evaluate the environmental performance of buildings and neighborhoods across the whole life cycle, which can occur anywhere and along with a product or service's value chain to make decisions in the building industry (Bishop et al. 2021; Bueno and Fabricio 2018; Obrecht et al. 2020). The four processes of LCA are goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. LCA has been utilized for assessing the building industry since the early 1990s, and then it has evolved and extended (Al-Ghamdi and Bilec 2017). Many green building rating systems employ LCA to evaluate environmental targets nowadays. For instance, in 2009, LCA was added as a guide credit to leadership in energy and environmental design (LEED), is the world's most widely used green building rating system (Lu et al. 2017). Construction materials and assembly of a project are analyzed through embedded impact during pre- and postoperation while investigating the energy usage by operational impact during operation (Al-Ghamdi and Bilec 2017).

Table 1. Five most extensive strategies for BIM–LCA integration

Strategy	Description
BOQ export	The integration process is by exporting BOQ from BIM platforms to different applications. This strategy is the most widely used in current practice
IFC import of surfaces	In the particular LCA tool, the engineering importing BIM model remains "as is." The BIM model is typically transmitted using an open interchange standard like IFC; however, original BIM file formats are feasible based on the characteristics provided by LCA programs. The LCA performer will relate the building elements to predefined LCA profiles obtainable in the LCA platform databases using the imported data
BIM viewer for linking LCA profiles	The assigned LCA profile is at an intermediate stage in BIM Viewer tools. This necessitates using an IFC file to export BIM models from aboriginal BIM applications. The LCA performer or BIM specialists could specify LCA profiles for building elements using a particular BIM viewer with functionality for the earlier purpose and a group of possible LCA profiles. In parallel, transferring all geometry data accompanying LCA profiles is to a specialized LCA software. LCA computation is conducted in an LCA program using these LCA profiles, followed by result analysis and visualization
LCA plug-in for BIM software	Using appropriate LCA plug-ins aims to maximize the number of phases of finalizing design processes inside the original BIM platforms. Within the native BIM environment, LCA profiles can be assigned to BIM objects using these plug-ins. The LCA plug-in handles all subsequent processes, including computation, result visualization, and analysis. As a result, the specialized LCA program is no longer used, and a plug-in is instead used
LCA-enriched BIM objects	As a result, the LCA profiles are linked to the engineering and material data in the BIM platforms almost immediately. Computation and analysis with a plug-in in the specialized BIM program, or export to specialized LCA software, could be included in the next stage of this workflow. The last strategy has the advantage of making information on the environmental implications to be assessed concurrently with project development

Source: Data from Wastiels and Decuypere (2019).

Table 2. Automatization method degrees for integrating LCA with BIM

Degree	Method description
Manual	Transferring data manually entails the copy and pasting information between files. LCA specialists are required to position the information correctly. Most information transfer between BIM and LCA technologies is still manual. This method is time-consuming, and mistakes are possible
Semiautomated	This typical method happens automatically also, through sharing and supplying the information, while some human dealings are necessary for exports and imports. Some exported data are from BIM platforms in the LCA program. However, the data are processed more during many circumstances; the additional required details are not obtainable in the BIM system. This method necessitates some programming knowledge. The improved scripts promote the linking of several platforms and employ them as a foundation to construct new LCA programs or plug-ins
Fully automated	It is what is known as "one-click" integration. The information transfer is completely automatic. Employing LCA plug-in platforms is the most used, but there are a few examples of researchers building scripts via integrated multiple platforms. Using plug-ins produces consequences quickly, but these platforms have several restrictions related to preliminary information only, or there is no way to reset the frameworks inside LCA research

Sources: Data from Bueno et al. (2018) and Obrecht et al. (2020).

Table 3. Requested information for each phase of the LCA

Life cycle phases	Requested information	Resources	Linking with BIM
Product phase	Implications of materials on (environment-quantity)	Databases, environmental product declaration (EPD)	Separate or linked
Getting to the construction site	Means—distances	Overall hypothesis—spreadsheets—separate platforms	Separate
Construction phase	Energy—materials	Spreadsheets—separate platforms	Separate
Use, repair, maintenance, replacement, refurbishment	The reference service life of materials—scenarios (end of life, maintenance)	Databases—worksheet—separate platforms—overall hypothesis	Separate
Energy	Energy usage	Computation by plug-ins—exporting to separate platforms	Separate plug-in incorporated
Water	Water usage	Databases—worksheet—hypothesis	Separate
Disassembly	Energy and materials needed for disassembly	Databases	Separate
Disposal	Distances—means	Worksheet—separate platforms—overall hypothesis	Separate
Waste	Energy and material for waste processing	Worksheet—databases—hypothesis	Separate
Emission	An emission caused by disposal	Worksheet—databases—hypothesis	Separate
Gains—burdens that extend beyond the system limits	End-of-life scenarios—energy and material to process waste—possible profits	Worksheet—databases—hypothesis	Separate

Sources: Data from Lützkendorf (2018) and Mohammed (2022).

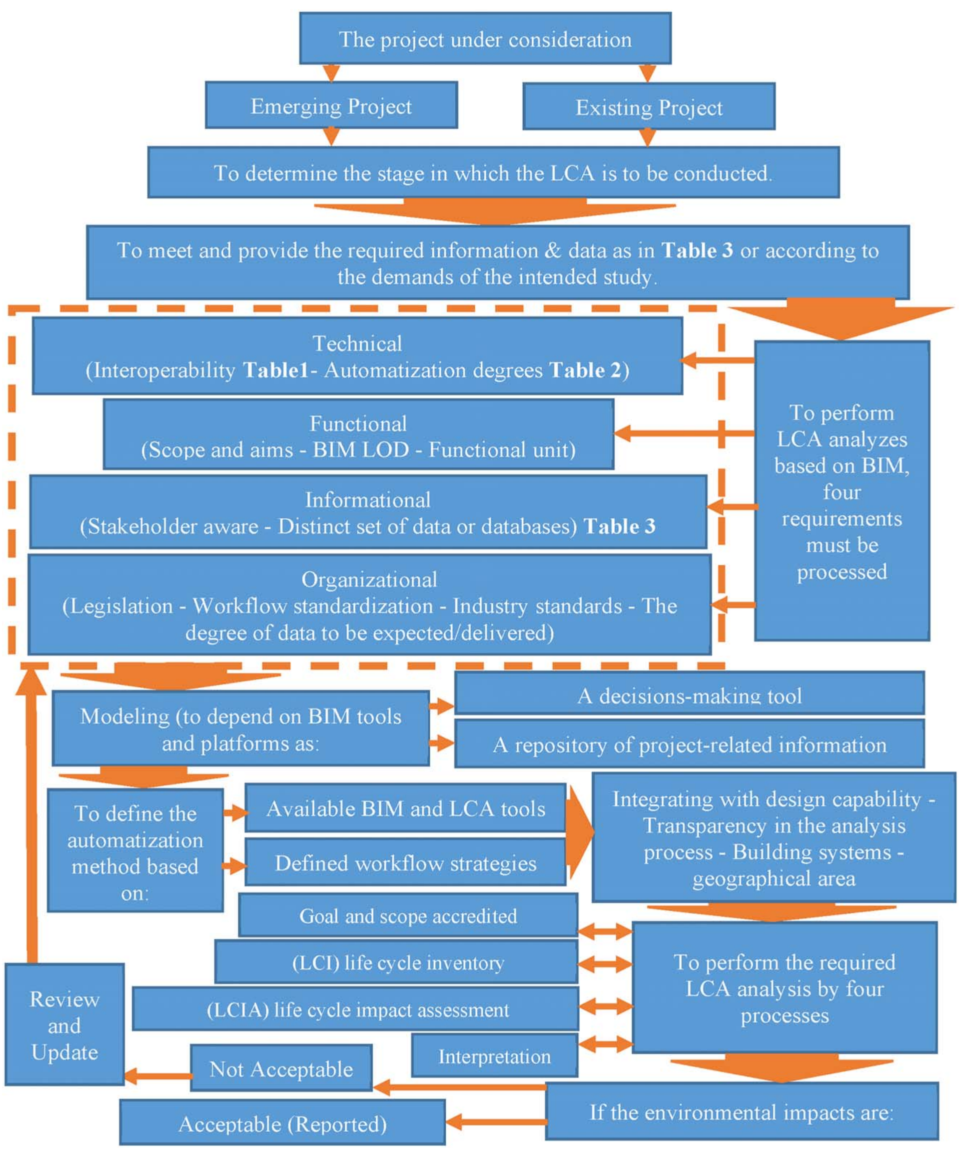

Fig. 5. Proposed process map of an automated LCA through BIM.

Table 4. Estimation of the importance of the three stages of the proposed map and its steps by analyzing the AHP results via SPSS

	Descriptive statistics			(One-sample t-test) left tailed		
	Mean					
The process map stages	Statistic	Std. error	Std. dev. Statistic	The alternative hypothesis	t^* (p-value, $n-1$)	Decision
Preparation and equipment	4.88	0.05	0.33	5	−1.292	Accepted
Modeling and qualification	4.92	0.04	0.27	5	−0.516	Accepted
LCA analyses	4.94	0.03	0.24	5	0.000	Accepted
Legal N (sample)	50 participants			To accept the alternative hypothesis, use the Likert scale (5 is a strongly agree)		

Note: If the test statistic t^* is greater than t from right-tailed or smaller than t from left-tailed, the null hypothesis is rejected, thus accepting the alternative hypothesis.

Table 5. Sequence of the three stages of the process map by analyzing the AHP results via SPSS

	Descriptive statistics			(One-sample t-test) two-tailed		
	Mean					
The process map stages	Statistic	Std. error	Std. dev. Statistic	The alternative hypothesis	t^* (p-value, $n-1$)	Decision
Preparation and equipment	1.06	0.03	0.24	1	−25.938	Accepted
Modeling and qualification	1.94	0.03	0.24	2	0.000	Accepted
LCA analyses	3.02	0.02	0.14	3	54.000	Accepted
Legal N (sample)	50 participants			To accept the alternative hypothesis, use the Likert Scale (5 is a strongly agree)		

Note: If the test statistic t^* is greater than t from right-tailed or smaller than t from left-tailed, the null hypothesis is rejected, thus accepting the alternative hypothesis.

Enhancement of Managing LCA Data and Simulating Its Results

As a result, visualization of LCA outcomes became increasingly significant to assist in explaining and making decisions, which serves as a foundation for future developments of intuitive visualization and design consistent with LCA outcomes. Evaluating material and energy flows is at several stages of the life cycle, including the phases of manufacturing, construction, usage, and end of life (Motawa and Carter 2013). Undertaking the LCA of a building needs gathering enormous core information about the materials and processes, usage, end-of-life phase, and so on (Lu et al. 2017). That is a very requisite and time-consuming step. BIM can be employed to decrease the time and effort required to perform LCA analyses, as shown in Fig. 2. Environmental hotspots can be identified and mitigated throughout the design process or all stages by combining LCAs with parametric design tools such as BIM (Najjar et al. 2022; Obrecht et al. 2020). The purpose of the comparison was to assess the LCA software tools available to project designers. Three software LCA tools, namely, Athena, Tally, and SimaPro, were used to do an entire-building LCA in a massive hospital building. The most important conclusion is to determine the discrepancies in the results and provide direction for designers and LCA practitioners (Al-Ghamdi and Bilec 2017). Finally, the limitations were that the geographical data for three tools were not available, it was difficult to determine the accuracy of the outcomes, and there were rooted problems with specifying the processes of available life cycle units with materials. In addition, each LCA tool uses information from diverse sources, which adds to the suspicion amount.

Role of BIM in Managing Data

BIM comprises a combination of policies, processes, and technologies permitting various stakeholders to collaborate virtually on designing, building, operating, and retrofitting projects (Antwi-Afari et al. 2018). Geometric or nongeometric properties can be found on parametric objects in BIM with semantic, functional, or topology information (Lu et al. 2017). The BIM model primarily comprises data on the quantity and quality of materials used to compute embodied environmental consequences. Hence, supplemental data on environmental impacts and other LCA study inputs should be incorporated into BIM to reduce LCA effort (Obrecht et al. 2020). As shown in Fig. 3, the BIM-based solution aided in the most accurate, timely, and appropriate data exchange between project participants and the earlier creation of crucial data concerning programming, logistics, design detailing, and coordination, all of which contribute to significant value generation during the later production stages. Eventually, this indicates BIM's importance in human activity entails broad process improvements in buildings. In large-scale projects, the quantity of data traffic and the value of systems for managing such data would increase.

BIM to Optimize Decision-Making and Implementation of Success Factors Supporting LCA

During the total development cycle of any investment project, decision-making for the feasibility of location, design, or investment is the most significant step through the preinvestment phase. During the construction phase, decisions about addressing technical and transportation issues and using the available construction site are made. While the operational stage, decisions about possible extension, rehabilitation, or renovation are made (Lützkendorf 2018; Nowak et al. 2016). Accordingly, the issues and the decision-making circumstances need up-to-date, accurate, and complete data. Conflicts arise because of many participants in the construction project, necessitating decisions to be made even before the documentation is completed. The problem of data incompatibility in the construction industry appeared to be solved by BIM. As it found out later, it may be able to cure a lot more issues than was first thought. The decision-maker is responsible for describing participants' choices using a mathematical or geometrical model of the decision dilemma. After that, a simulation is run based on the model's data, providing options and solution variations to the decision-maker for approval (Lützkendorf 2018). The decision-maker gets an application with a mathematical issue model executed by interactive decision support. Then, the decision-maker converts participants' choices into relevant and targeted points and inserts information into the application to obtain the optimized result. The decision-maker can familiarize with the region of significant considered solutions by entering further targeted points, obtaining consequent solutions, and then determining the optimal variation based on participants' knowledge and experience (Nowak et al. 2016). This technique allows the decision-maker to participate in the decision-making process and protects us from overlooking the alternative that is most suitable for the choices of decision-makers. A previous case study was on a suggestion for a typical multistory office building in Brazil, which considered two construction technologies during the design phase (concrete or steel) (Najjar et al. 2022). This study examines LCA from a construction standpoint, supporting decision-making and sustainable building design in the construction industry. The BIM utilization benefits in making decisions during facility management are enormous, such as "as-built" (historical) documentation, maintenance warranty, and service data; quality control, evaluation, and monitoring; and management of energy, environment, emergency, or retrofit planning. Practitioners can better forecast the likelihood of successful BIM execution and take the required procedures to avoid project-based BIM failure by establishing a shared set of crucial success factors (Cavka et al. 2017). Besides, practitioners who successfully utilize the standard set of influential success factors within projects may obtain a competitive advantage in qualifying a BIM model for LCA analysis. Many alternatives concerning weak execution have concentrated on either technical difficulties, such as software cost, software interoperability, and employee training, or nontechnical problems, such as contracts, legal uncertainties, project delivery, workflow disruption, and cultural change. However, fixing these difficulties will require a more in-depth understanding of the critical success factors used to assess the success of BIM implementation. As shown in Fig. 4, these factors are the few core areas of activity where beneficial results are required for a manager to undertake LCA and achieve the priorities. As a result, such factors play a critical role in managing decisions and can be used to categorize, evaluate strategic goals in managing organizations, and measure organizational results, LCAs, and actions.

Strategies of Integration and Overlap between BIM and LCA and the Requirements of These Strategies toward Extensive Integration

Several studies have classified the integration and overlap between BIM and LCA. One of them suggested two alternative integration methods for BIM and LCA (Antón and Díaz 2014):

1. The first method includes directly accessing BIM model data to measure a building's environmental performance. Information is extracted from the BIM model by data-sharing format, the Industry Foundation Classes (IFC). Enabling actual-time comparison of project options is by eliminating the step of inserting information manually. Establishing this strategy has not been done entirely yet.
2. The second method requires environmental attributes to be included in BIM objects. Environmental features would have to be capable of evolving in line with the project's development, and there are still challenges with how to add data on maintenance, transportation, and so on.

Another study presented BIM–LCA integration development through three proposals or three stages (Soust-Verdaguer et al. 2017):

1. The first incorporates BIM as a tool to quantify material and building elements during the LCI phase.
2. The second utilizes BIM to organize and quantify construction components and materials, besides incorporating environmental data into BIM software or energy building evaluation.
3. The third includes the evolution of an automated process linking different software programs and pieces of information.

The study adopted the subsequent proposed division and is the most extensive. It divided BIM–LCA integration into five strategies according to the possible workflows for this integration, as presented in Table 1. These strategies address the potential classifications of all integration processes.

BIM is a component of the primary storehouse of data utilized within LCA analyses and is considered a pillar of the integration process that exchanges data between two distinct technics or methodologies. Individual scenarios differ based on the information obtained and the degree to which integration between the BIM and LCA platforms is automated. LCA analysis comes with its collection of requirements (Bueno and Fabricio 2018; Obrecht et al. 2020). The analysis is a well-known method that was formed independently of BIM. The personnel will need some prior understanding of the procedure and relevant regulations to accomplish analyses. In light of this, the current study examined the (technical–functional–informational–organizational) requirements that BIM tools must meet, necessary, need, or rely on when attempting to integrate LCA and BIM cooperatively.

Technical Requirements of BIM and LCA Integration

The technological needs observed for integrating LCA and BIM are in two trends. The first trend is integration as interoperability; the integration process was categorized, as shown in Table 1. Sharing data via bill of quantities (BOQ) is the most usual link between LCA and BIM technologies (the first strategy). Using plug-in tools is the second most popular integration (the fourth strategy). The second trend, as shown in Table 2, is the automatization degrees of the integration process; if the information is imported into the LCA tool manually, which is the most common method, the procedure is time-taking and prone to errors (Alreshidi et al. 2017; Singh et al. 2019). As a result, suggestions exist for a way to automate the exchange procedure (Jalaei and Jrade 2014; Soust-Verdaguer et al. 2017). Also, various studies have tried to promote BIM and LCA integration to some extent. BIM–LCA integration as the fourth and fifth strategies comprises two general methodologies for automation degrees. The benefit of the fifth strategy is integrating LCA data into the BIM model directly. So, incorporating both generic and product-specific information is very beneficial. Environmental information is directly integrated within BIM, resulting in real-time knowledge about the consequences of the environment, but it has the hazards of making massive and slow files. Executing the computation and analysis is using a plug-in or exporting data to LCA software. In other research works, when Excel-based methods calculated the environmental consequences, extra data connection was also done (Bueno and Fabricio 2018; Obrecht et al. 2020). Most of the information of the BIM model pertains to the amount and materials' quality. These are crucial factors to consider when calculating embedded environmental implications. Using building energy should be specified to get input for the operational energy requirement (Motawa and Carter 2013). Energy computation (EC) is done within a particular platform, such as a plug-in, or integrated into the BIM tool. The implemented EC standards of the specific location affect the selection decision of employing the EC tool. Another aspect is the flexibility with EC and BIM technologies that can be integrated (Obrecht et al. 2020; Volk et al. 2014). As a practical case study for automating the process of information insertion and extraction to or from the model by incorporating applications of current and centralized tools (Autodesk Revit, Dynamo, and Microsoft Excel) to decision-making in the early design stages, they were utilized in an existing social housing model to simulate the tool behavior and outcomes rendered in an actual project (Bueno et al. 2018).

Functional Requirements of BIM and LCA Integration

Specifying the data needed from BIM is across the functionality demanded through the LCA analysis (Volk et al. 2014). The accurate data required to undertake LCA analyses must comply with the study scope and aims, besides establishing the data structure during the design phase. The data structure, on the other hand, allows information sharing between programs (Cavka et al. 2017). Modeling the model must be accurate to support essential functionalities. Such functionalities could be built into or added to the BIM tool as separate information, programs, and plug-ins. The first task in LCA is to determine the study functional unit. In most common analyses, selecting such a unit is the entire project, with the findings standardized by area or individual building elements. On the other hand, determining the precision of the information is based on the design phase and the level of detail (LOD) at which the BIM model is created. Each specified study has the necessitated data restricted by the requested life cycle phases to evaluate.

Informational Requirements of BIM and LCA Integration

The interoperability of the tools as technologies is inextricably related to the informational requirements (Khaddaj and Srour 2016; Volk et al. 2014). In addition, the integration process must be managed properly so that all stakeholders are familiar with the types of data that must be given and supplied. Each phase necessitates a distinct set of data or databases, as given in Table 3, which lists the information needed at each phase of the life cycle. The project design stage determines the precision and the information quality. There is no universal agreement on characterizing the design phase; each country's definition is different. Because the LCA is utilized early in the design process, there is an even greater requirement to link BIM to the LCA platforms. However, the meaning of the phase of an initial design is still up for debate; the LOD of a BIM model is related powerfully to the design stages. The LOD specifies these geometric and nongeometric characteristics in a model (Antwi-Afari et al. 2018).

Organizational Requirements of BIM and LCA Integration

The organizational criteria must be met while adhering to all applicable laws and regulations (Obrecht et al. 2020). Standardizing the application of BIM tools within existing projects imposes adjusting legal and organizational frameworks (Khaddaj and Srour 2016). The requirements related to integrating and automatizing the relationship between LCA and BIM, as indicated in Table 1, are closely associated with organizational elements and workflow standardization. However, individual techniques can be developed to link BIM with LCA. The widespread use and automatization of LCA within BIM-based workflows necessitate establishing industry benchmarks. Benchmarks are necessary for LCA analysis and BIM models concerning ontology, information building, and the degree of data (to be expected/delivered) at a given design phase, among other things. However, as evidenced by a recent international study of building design professionals, implementation in everyday industry practice remains a struggle (Antwi-Afari et al. 2018).

Proposed Process Map for Managing the Automatized LCA Based on Its Integration with BIM

From the aforementioned, based on what was accomplished previously in the inductive approach, besides the analytical approach outcomes, as shown in Fig. 1, the study can deduce a process map that is a visual representation of the workflow planning and management techniques used. It can be used in any business or organization to indicate who and what is involved in a process and could reveal areas of possible improvement. Process mapping is used to acquire a better understanding of a process. Process maps are used in BIM to transmit functionality-related process information. Process maps define roles and actions for a particular task or functionality and describe the flow of operations within a specific assignment, the responsibilities of the actors, and the data required, generated, and utilized (Volk et al. 2014).

The objective of the proposed process map, as shown in Fig. 5, is to facilitate and support the implementation of LCA analyses in an automatized manner based on BIM by

1. addressing LCA and integration difficulties with technologies such as tools and software associated with BIM by manual methods;
2. decreasing manual methods in LCA-related calculations to save time and effort and reduce errors in transferring, exchanging information between programs, and entering the information;
3. reducing as much as possible human interference in procedures and processes and speeding up and facilitating dealing with different platforms and integration between them; and
4. facilitating and supporting the reimplementation of calculations at any time to either make updates and adjustments, verify the results, or compare the results of the tools used to perform LCA analyses.

The structure of the proposed map consists of three stages (preparation and equipment, modeling and qualification, and LCA analysis).

First Stage Is the Preparation and Equipment

1. To distinguish the project type, whether it is new or existing, because this will affect the specifications of the BIM model, as shown in Fig. 4, that will be modeled at the LOD level, the quality and approval of the design for the project, the effort expended, and the available freedom degrees in addressing the four requirements that BIM tools must meet when trying to integrate with LCA.
2. To determine the stage required to implement the LCA or all stages of the project life or study one of the factors of the LCA separately, thus defining the purpose and scope of the study accurately.
3. To meet and provide the required information and data, as given in Table 3 or according to the requirements or needs of the intended study.
4. Based on the aforementioned, to conduct BIM-based LCA analyses, the four requirements that BIM must meet when performing these analyses are addressed with the least time, effort, and the highest concentration of data and information required

solely. Also, dispensing with everything that has no role in the demanded processes and analyses is as follows:

- Technical requirements: to process interoperability and information exchange between BIM and LCA tools (Table 1) and to define the degrees of automatization according to the workflow required to carry out the intended analyses (Table 2).
- Functional requirements: to ensure that the accurate and required data for the LCA are consistent with the scope and aims of the study; to identify the LOD level of the BIM model that aligns with the LCA analysis required; and to determine the functional unit accurately for saving time and effort and achieving the level of LOD that supports it and provides the information and data required for the LCA.
- Informational requirements: to raise stakeholder awareness about the required information and make it available; also, to supply tools and software with such information before carrying out LCAs; and to provide distinguished information and databases that differ according to the different stages of the project life cycle (Table 3).
- Organizational requirements: to meet the organizational criteria while adhering to all applicable laws and regulations; to adjust legal and organizational frameworks with the workflow for standardizing the application of BIM technologies in projects; to adhere to industry standards whose implementation in everyday industry practice remains a struggle; and to adhere to standards, which is necessary for both LCA analyses and BIM models in terms of ontology and information building at a given design phase to fulfill the degree of data to be expected and delivered.

Second Stage Is Modeling and Qualification

The modeling process at this stage is not the same as ordinary modeling on BIM; it requires fulfillment of all the four previous requirements in the targeted model to be prepared and equipped to perform LCA analyses, as shown in Figs. 3 and 4.

1. The model is to be treated as a tool to improve decision-making, as shown in Fig. 2, and as a repository for storing, retrieving, and processing information on which computations and calculations of LCA analytics will be built.
2. The method of automatization is determined based on choosing the BIM and LCA tools that will serve the required analyses and accurately give the desired results. Here, it is necessary to define the most significant characteristics of the assessment tools, namely, integration with design capability, transparency in the analysis process, incorporation of building systems that can be included in the LCA (structural, architectural, finishes, mechanical, electrical, HVAC, plumbing, etc.), the geographical area covered, and user LCA experience required and to identify and define workflow strategies, namely, BOQ export, IFC import of surfaces, BIM viewer for linking LCA profiles, LCA plug-in for BIM software, and LCA enriched BIM objects.

Third Stage Is LCA Analyses

This stage depends on the first two stages; the preparation and equipment were completed to implement the calculations, the model was built, the potential degree of automatization was identified, and the workflow strategy for performing the LCA was determined. During its four steps,

1. the first step (the accredited goal and scope) depends on what has been determined concerning the functional unit and modeled life stages;
2. the second step, LCI, requires generating BOQ and defining the databases that contain the environmental information that serves the BIM tools selected from the modeling stage to implement LCA computations and calculations, as shown in Fig. 3 (the tools vary concerning the LCA databases handled);
3. the third step, LCIA, is to implement the methodology of the selected instrument (LCA tools and software) to facilitate the characterization of environmental stressors that have the potential to contribute to impacts; and
4. the fourth step (interpretation) is to clarify the constraints, assess the evaluation considering the tests (completeness, sensitivity, consistency), present the LCA results, reach various conclusions and decisions, and clarify operational and embedded environmental impacts.

Finally, if the environmental impacts are acceptable, they are documented in a report for approval and review before activation. The revision, update, and retreatment are performed if not accepted. It starts with the fulfillment step of the four requirements in the first stage and then advances through the stages and steps of the proposed map another time until the result of LCAs is reliable and accepted.

Validity Evaluation of the Process Map

Data were collected and analyzed in two rounds; the first round was an exploratory study aimed at the following:

- to specify the number of participants and their qualification level in the targeted study about integrating BIM and LCA; and
- to verify whether a point or an element mentioned around BIM integrated with LCA is not addressed in the research.

Eighty individuals were invited for the first round. The number of participants in the exploratory study was 69, and a preliminary questionnaire was distributed to them. The questionnaire consists of the following: the first part is an introduction and an overview of the research topic. The second part consists of five questions related to the advantages of the subject and field of study, disadvantages, opportunities available on this subject, the BIM's platforms and tools used, and whether they dealt with LCA or each of its components. The second round, using AHP to assess the validity of the proposed map and whether it achieves advantages, addresses the negatives and creates opportunities to facilitate and support the implementation of LCA analyses in an automatized manner based on BIM (Jin Lin et al. 2015; Saaty and Vargas 2012). The 50 participants' responses in the first round were preferred. These participants were the ones who participated in the second round, which was about this proposed process map. It was introduced in questionnaires and interviews to evaluate the importance of its stages and application mechanism validity for achieving the automatized integration of LCA and BIM to enhance and optimize LCA analysis. If there are other stages and guidelines, as shown in Fig. 5, they will need to be added, edited, deleted, or reformulated. Experts and practitioners conducted questionnaires and interviews in the sustainability and BIM fields. There were 50 participants (14 academics, 15 architects, 12 building consultants, and 9 construction managers). The study utilized the AHP, which was created to answer complex issues or queries involving various criteria and principles, besides evaluating the consistency ratio to ensure that judgments or views are accurate (Goepel 2013). The AHP results from the questionnaires were reviewed and evaluated according to the expertise classification of participants via the SPSS (Statistical Package for the Social Sciences) program to execute a (left-tailed) one-sample *t*-test, as given in Table 4, to estimate the importance of the stages and their elements and a two-tailed *t*-test to order these stages, as given in Table 5.

Generally, building information models have no information or inputs for a complete LCA to overcome such a lack; numerous other required actions are to be considered for having information itemized when the BIM model is finished. This study identifies, explains, and builds the basis of the relevant workflows to accomplish the LCA related to different projects, which can be implemented in the BIM environment. The proposed process map bridges the information gap between the exploited BIM parameters and the LCA information demands through possible automation. That leads to minimizing the quantity of time consumed and errors during activities, strategies, or assembled assumptions or being dependent on random automated methods.

Results and Discussion

From the survey study outcomes, the proposed map is detailed, and it supports and helps to implement the LCA in a systematic and structured manner, as shown in Fig. 5. The map encourages and improves the reimplementation and practice of LCA calculations several times to reach the level of acceptable environmental impacts. Such impacts regarding new buildings calculate the actual and operational influences upon the environment that will turn up or happen within reality in the case of existing buildings. The map improves the level of the construction industry, besides working to reduce the harmful and unhelpful environmental impacts by checking the project based on the stages and detailed steps within the map by the manner of its application and operation. The map supports the standardization and alternative strategies of the workflow. The map creates a BIM model with new features that can be relied upon in all construction industry calculations, not just LCA. The stages of development, preparation, and modeling are documented as a scenario that can be reformulated again or identify defects or weak points in implementing the proposed map with each type of different LCA calculation.

At the practical application level, the study deals with how to employ building information modeling programs to automatically conduct a life cycle assessment and reduce human errors and manual methods. These analyses focus on all conditions of materials and energy, and they invent them and their cumulative and potential effects on the environment and users throughout all life stages of a building. Thus, a proposed process map as the basis for the workflow and its alternative strategies is to achieve that automatized integration between life cycle assessment and BIM. Because LCA analyses depend on a tremendous amount of information, manually calculating these analyses and manually exchanging information among programs make calculations inaccurate and an incomplete entry of all the required data to perform LCA calculations. Thus, that reflects upon the quality and accuracy of the analyses of materials, energy, environmental effects, cost, and quality of projects. Consequently, the created BIM model for implementing and managing the project will acquire new features and have a critical role in managing LCA analysis in a comprehensive automated manner. This new model will facilitate the recalculations at any time, allow retrofits, and verify and compare the potential environmental consequences.

The limitations and significant challenges are the capacities of each organization or person to supply the platforms, environmental databases, and hardware that will handle the planned automatization process from BIM and LCA integration. The second challenge includes the time needed to link and integrate BIM and LCA. The third challenge is the people's capacity to handle the volume of information and data within the platforms before linking and integrating BIM and LCA and the time required to achieve it. The fourth challenge is that the rating systems give a small percentage or a few points to the LCA, despite its enormous importance and benefits in the construction industry. Presently, it is crucial to mention that there are issues regarding the constraints of the environmental data that might be correlated with LCAs (van der Giesen et al. 2020; Najjar et al. 2022). However, the platforms provide information about the relevant environmental databases. Very few constructive alternatives are available to connect them to the building systems used by the BIM model, as shown in Table 3. As a result, the user is obliged to guess which building component type is the most similar, which may cause variations in the results. The final results must consider that restriction, which might not be definitive in the future.

There are previous unstructured attempts to effectively integrate the LCA study into the BIM-based design workflow in a world where most data transmission between BIM and LCA has been done manually until now, as shown in Tables 1 and 2 (Hollberg et al. 2021; Obrecht et al. 2020; Röck et al. 2018; Wastiels and Decuypere 2019). This allows for more efficient LCA analysis depending on accessible building data and reduces the need to manually input information into the established simulation platforms of building systems (Obrecht et al. 2020). Consequently, the study overcomes this by clearly structuring the proposed map and explaining its procedures, steps, and three stages in detail.

Some individuals believe that the BIM and LCA integration is merely a technical need, while others believe it involves organizational, informational, and functional prerequisites (Cavka et al. 2017; Khaddaj and Srour 2016; Volk et al. 2014). The study sought to address this controversy by addressing and achieving all through the proposed process map, as shown in Fig. 5.

Numerous studies have stressed the importance of establishing BIM and LCA integration early in the design process while adjustments to the design are still available (Bishop et al. 2021; van der Giesen et al. 2020; Hollberg et al. 2021; Lützkendorf 2018; Najjar et al. 2022). As a result, the role of LCA in utilizing design rather than documenting the outcomes and implications through the proposed process map must be emphasized and activated. The procedures in this proposed process map illustrate how to utilize the LCA at any project life cycle phase.

However, other studies confirmed that the integration between BIM and LCA should be established during all life cycle stages for four reasons:

1. The analysis uses several LCA tools and methods to account for the entire cradle-to-grave life cycle, encompassing material production, maintenance and replacement, and final end of life, which includes the energy required at all phases of the life cycle (Al-Ghamdi and Bilec 2017).
2. It could model any project at any stage of its life cycle and control it by the LOD of the model.
3. The benefits of utilizing BIM in facility management appear to be enormous, such as important "as-built" (historical) documentation, maintenance warranty and service data, quality control, evaluation and monitoring, environmental, energy, and emergency management, or retrofit planning, thereby minimizing errors and financial risk (Khaddaj and Srour 2016; Volk et al. 2014).
4. How BIM can help manage and optimize demolition and construction waste through life cycle environmental impact assessments (Jalaei et al. 2019).

This technique or strategy is still in its initial stages, even though the study identified numerous distinct methods for incorporating BIM and LCA (Bueno et al. 2018; Mohammed 2022; Obrecht et al. 2020). The study shows that the core integration process challenges are

- to establish seamless and automatized data sharing among BIM and LCA technologies, whether they are utilized as separate files or as part of the BIM environment;
- to create databases that are both semantically and ontologically compliant with the BIM environment and harmonize with the aimed design phase; and
- to develop a synchronized LCA method promoting the specified definition of the inputs required.

By defining a standardized set of critical success criteria, practitioners can more accurately predict the likelihood of successful BIM execution and take the necessary steps to prevent project-based BIM failure. A BIM model may be qualified for LCA study by practitioners who successfully apply the standard set of influential success elements within projects, giving them a competitive edge. The automatization of BIM and LCA integration is still in its early phases, but it can be accomplished with the help of optimizing custom plug-ins or BIM tools, specialized LCA tools, and complicated scripts based on execution plans and process maps.

Conclusions

The main conclusion of this study is to establish a practical procedure and a strategic implementation plan as the basis of the workflow of LCA through a proposed process map. This map is used to conduct the LCA based on BIM to facilitate and support accomplishing LCA analyses in an automated manner that will be a path for their automatized integration later, which is the key aim of the study. This map overcomes and treats the obstacles of traditional or manual methods of implementing LCA and the consequences of human intervention in the computation and saves time and effort for decision-makers in the construction industry. Also, during the overlap and integration of LCA with BIM technologies, many difficulties have hindered automatizing the integration between them and affecting their result quality. Map validation is checked by the exploratory survey and then AHP through questionnaires and interviews, which verified that the BIM model acquired new attributes and will play an essential role in the LCA's accuracy, reliability, and comprehensiveness. This map reinforces the standardization and alternative workflow strategies, besides its interconnected stages as a scenario to conduct an automatized LCA within any project's life phase and guarantee LCA's quality. The role of the proposed map is to treat all of the aforementioned by achieving the four integration requirements primarily (technical–functional–informational–organizational) that were investigated and outlined. Thus, depending on BIM is a good repository for preserving and managing data and information and has an active role in optimizing decision-making and supporting environmental analyses. Besides, the five integration strategies between BIM and LCA are activated and employed according to workflows, possible methods, and automation degrees. So, the proper choice of BIM and LCA tools is the most effective action for calculating the analysis accurately, depending on identifying the stage for which the LCA analysis is required and determining the type of relevant information, databases, laws, and standards. Then, the model for the studied project is built based on the success factors of BIM implementation were collected, identified, and made the model ready to conduct the required and targeted environmental analyses. Then, all of this is linked to the known stages of LCA analytics execution, thus avoiding the failure of BIM-based projects and making them qualified for implementing LCA. All of this is to facilitate, support, and improve the automatization of LCA analyses in a more accurate and quality manner based on integration with BIM since there is a constant quest to make the integration process of LCA with BIM during environmental investigations more automated and the results of environmental impacts are more accurate, thoughtful, and reliable. Such environmental analyses play an important role in improving the performance of buildings, projects, and the construction industry throughout their lifespan and reducing their impact on the environment and users. Consequently, it will be possible to rely on this proposed map as a path toward increasing and encouraging LCA automatization operations in the future. In addition, as a future endeavor, social studies with LCA would be merged through BIM platforms that must be rehabilitated to include all indicators of the three sustainability aspects and all databases that serve tangible and intangible environmental calculations and impacts of LCA.

Data Availability Statement

All data, models, and codes generated or used during the study appear in the published article.

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