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Review

Recent Technological Advancements in BIM and LCA Integration for Sustainable Construction: A Review

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Abstract: In the high-energy, high-carbon landscape of the construction industry, a detailed and precise life cycle assessment (LCA) is essential. This review examines the role of building information modeling (BIM) software in streamlining the LCA process to enhance efficiency and accuracy. Despite its potential, challenges such as software interoperability and compatibility persist, with no unified standard for choosing BIM-integrated LCA software. Besides, the review explores the capabilities and limitations of various BIM software, LCA tools, and energy consumption tools, and presents characteristics of BIM-LCA integration cases. It critically discusses BIM-LCA integration methods and data exchange techniques, including bill of quantities import, Industry Foundation Classes (IFC) import, BIM viewer usage, direct LCA calculations with BIM plugins, and LCA plugin calculations. Finally, concluding with future perspectives, the study aims to guide the development of advanced LCA tools for better integration with BIM software, addressing a vital need in sustainable construction practices.

Keywords: building information modeling (BIM); life cycle assessment (LCA); sustainable construction; software interoperability; data exchange methods

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1. Introduction

Since the 21st century, the construction industry has consumed a great quantity of energy resources and produced significant greenhouse gases that have had a substantial negative impact on the environment. The Global State of Buildings and Construction report shows that the construction industry will account for about 35% of worldwide energy consumption and 38% of total CO_2 emissions in 2020 [1]. Life cycle assessment (LCA) is a strong tool for assessing the environmental performance of a product or process and is also used to compare environmental performance between similar products. International Standard 14040 [2] demonstrates that a typical LCA process consists of four phases: goals and scope definition, life cycle inventory (LCI) analysis, Life Cycle impact assessment (LCIA), and Interpretation [3]. However, LCA has a complex operation process, which consumes a considerable amount of user time, and the scope of application of the database is highly limited [4]. The development of LCA tools such as SimaPro, GaBi, Umberto NXT, and Athena has improved the efficiency and accuracy of environmental assessments of buildings, optimized the data analysis approach, and facilitated accurate quantification of environmental impacts [5]. However, often quality data extraction and inventory development are major limitations that lack accurate ways to accurately integrate building data information. Therefore, building information modeling technology (BIM) is very important to conduct a comprehensive life cycle assessment of buildings to improve environmental benefits.

BIM is an innovative technology used to analyze building information, enhance current communication processes, provide a collaborative platform, and support interoperability between different practice fields. The measurement of carbon emissions and the environmental impact of buildings can be provided by BIM because BIM can improve the reuse of information and provide project data directly, thus avoiding the uncertainties and inefficiencies associated with manual input [6]. The usefulness of BIM digital tools has led to continuous development research in this area, and the more widely used BIM software includes Autodesk Revit and Graphisoft Archicad. These software programs store graphical information about building elements and material properties, allowing users to visualize them.

Based on the characteristics of BIM digital tools that have the potential to reduce the additional workload of LCA and to accelerate the process and to simplify complex workflows, it reduces errors in manual calculation, analysis, and data collection, improving work efficiency [7]. However, different BIM software is not fully compatible with all LCA tools and is prone to data loss. There is a lack of research on the comprehensive analysis of BIM–LCA-integrated applications and the identification of parameters that affect the practical application of the software. In addition, previous studies have neglected several important metrics related to the performance of BIM–LCA integration methods. BIM-integrated LCA still suffers from unclear selection of software tools, uncertainty of interaction, and difficulty in selecting the degree of automation, which leads to limited optimization direction of BIM–LCA referenced scenarios, and it is difficult to have a clear cognition in defining and judging the adaptability in various scenarios. Therefore, there is a need for optimization directions provided for practical cases, working to enhance the interoperability and compatibility of BIM software and LCA tools. In response to the limitations that existed in the previous integration, it is necessary to explore the prospectivity of its future development, which is conducive to improving the accuracy and efficiency of the BIM–LCA integration framework. Herein, this review summarizes the characteristics of commonly used BIM software and LCA tools, providing an overview of the limitations related to BIM and LCA integration. The purpose of the study is to understand the software compatibility and interoperability of BIM-integrated LCA and to identify the features and drawbacks of each software application.

2. Methodology

This review uses PRISMA bibliometric statistics to analyze the progress of BIM software and LCA tools in order to explore in-depth the challenges and future perspectives of the integrated application of BIM software and LCA tools. The current systematic approach under the PRISMA perspective covers the critical analysis of key factors such as the integration of BIM software and LCA tools into the application, integration parameters, challenges, and future perspectives, as shown in Figure 1. Web of Science was used as the database for this review and Boolean operators were used in the ‘Title, Abstract and Keywords’ fields to search 23,843 articles on “BIM software” and “LCA tools”. The topics related to BIM-integrated LCA were filtered according to the purpose and scope of this review. Eligibility criteria provide the boundaries for evaluation in the system. According to the purpose and scope of this paper, the topics related to BIM-Integration LCA were screened to obtain the outputs 4686, 3566, and 9217 articles about integration applications, integration parameters, challenges, and future perspectives. By eliminating duplicates, a total of 13,617 articles will be obtained that fit the main exploratory direction of this review. The scope of this review only discusses academic papers whose type is article, English language, and published between 2006 and 2023. Thus, according to the PRISMA methodology, 6448 papers that did not meet the criteria were removed, including 4964 non-article types, 110 non-English types, and 1374 from years before 2006, and 7941 articles assessed for eligibility were passed. In this paper, VOSviewer 1.6.20 was used for (Figure 2a) integration application, (Figure 2b) integration parameters, (Figure 2c) challenges and future perspectives of the BIM software integration LCA tool, respectively. This review utilizes visual literature co-occurrence analysis to further analyze the frequency of co-occurrence of titles, abstracts, and keywords in the screened literature to determine research buzzwords. It can be seen that the popular words for integration application, shown in Figure 2a, include data, energy, structure, prediction, industry, user, and emission. Figure 2b shows the popular words for integration parameters, including efficiency, feasibility, scenario, energy, knowledge, database, accuracy, and distribution. In terms of challenges and future perspectives, framework, data, time, algorithm, network, accuracy, prediction, and sensitivity analysis are shown in Figure 2c. Ultimately, based on in-depth reading and VOS viewer analysis, 152 papers were selected as the scope of this review to be explored

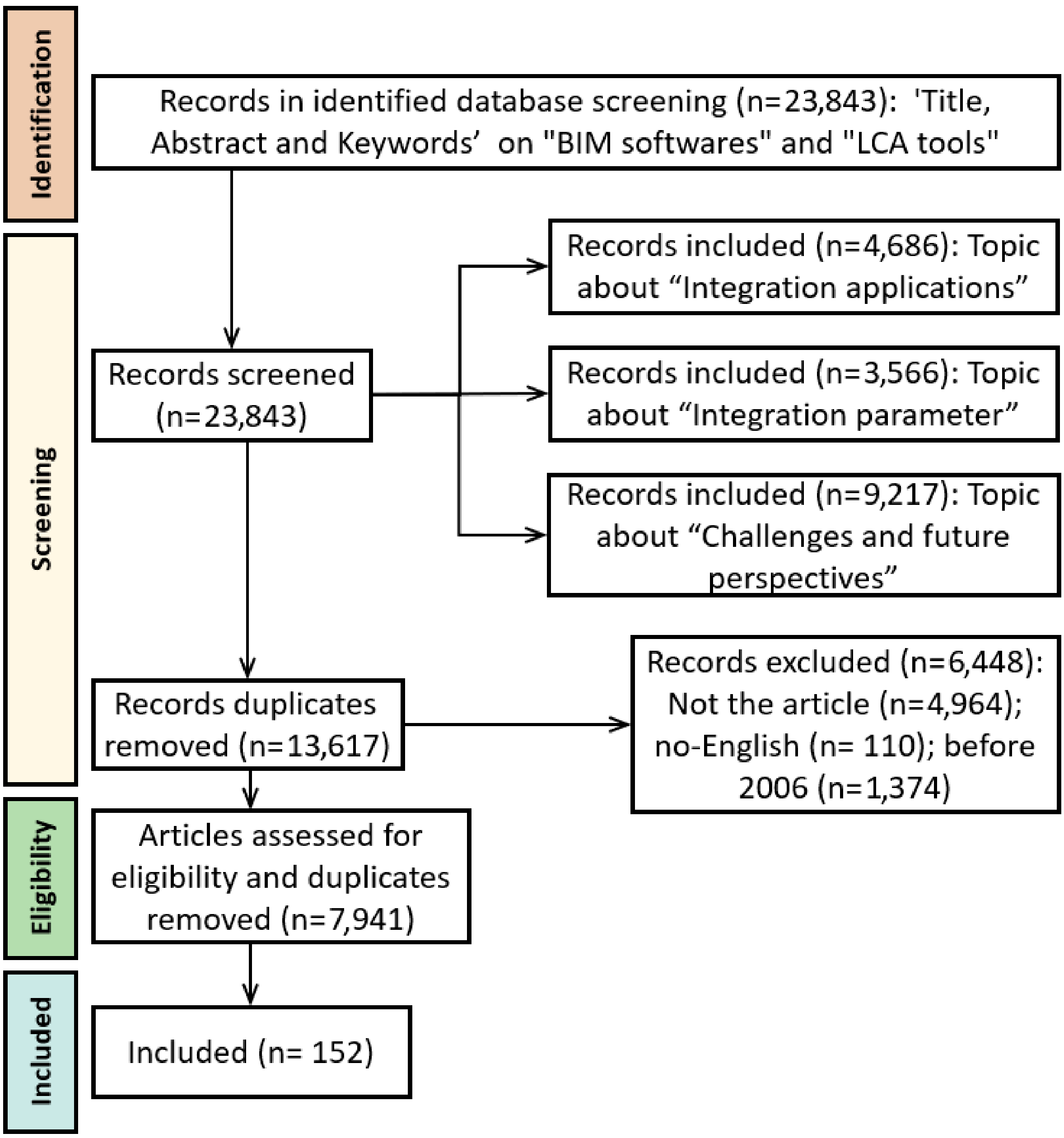

Figure 1. Data collection process for PRISMA.

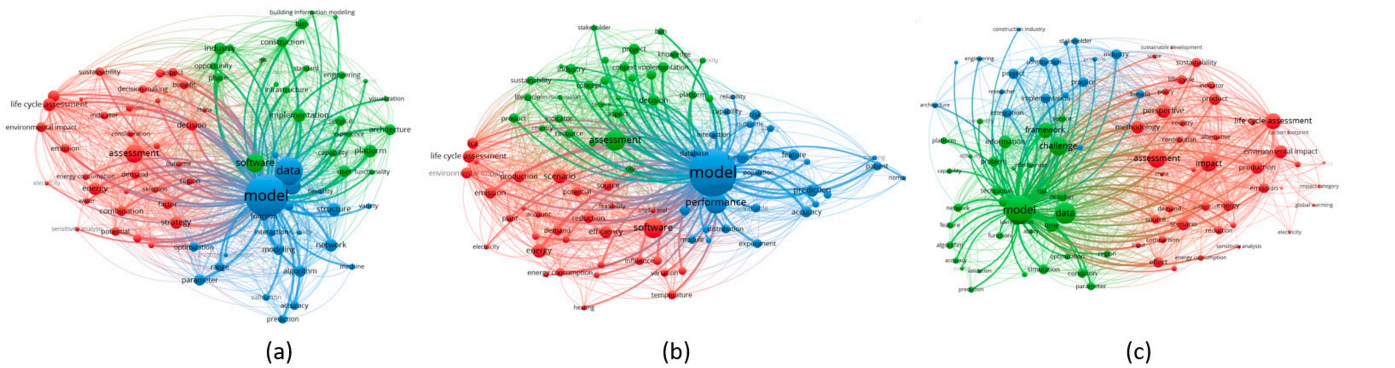

Figure 2. VOSviewer buzzword analysis (**a**) Integration applications; (**b**) Integration parameters; (**c**) challenges and future perspectives.

3. BIM Software and LCA Integration

3.1. BIM 3D Modeling Software

BIM 3D modeling software provides unique smart digital modeling and information management and therefore is recognized as the technological step of a BIM process [8]. BIM software has the potential to facilitate building environmental performance assessment and reduce the additional workload of LCA, and speed up the process [9]. BIM software can provide virtual models containing graphical information, construction material, and component data. Table 1 shows three common BIM software: Autodesk Revit, The Beck Group Dprofiler, and Graphisoft ArchiCAD, and describes the features and limitations of this software for LCA applications.

BIM is supported by the program Autodesk Revit, which also creates and maintains data on building structures [10], considered the best BIM software [11]. Revit software provides tools for building elements, public utilities, and structural engineering and excels in designing structures with complex geometry and high computational efficiency for a wide range of applications. Revit runs faster and more efficiently, and can import, export, and set links to data in common formats [12]. 3D visualization provides greater insight into project features prior to implementation. Higher levels of detail can be recorded during modeling, providing accurate rebar items. When creating models, Revit software cuts down on repeats and measures how items affect the surroundings. However, the more general design tools not built into Revit make it more difficult to design projects accurately than using software created specifically for design. Therefore, the use of Revit and Excel to calculate energy consumption and CO_2 emissions may face time-consuming problems to solve. The correct mapping between the Revit material data source and the LCA database is an important factor in reducing time consumption, since there is a mismatch between the Revit material list and the ecoinvent LCI database, and the units defined are different. Revit software still suffers from software interoperability issues, and the type of information and reports generated are deficient in the tasks that Revit performs [13]. Because of this, the portable document files (.pdf) and extensible markup language (.xml) files available for Revit calculations are very limited because Excel or other number-based programs cannot properly recognize data saved in code and text-based formats. In addition, Lu, Jiang [14] stated that Autodesk Revit loses components and information when transferring to Glondon GTJ2018. Therefore, there is a possibility of data loss in the transfer of Revit data to the LCA model. The method of matching data between Revit and Athena has different limitations, so it can only be modeled for two individual components (walls and doors) and cannot be applied to the whole building.

Building modeler DProfiler was developed using a tool that automatically exports BIM data to an energy modeling application [15–17]. DProfiler provides detailed feedback on material quantities and energy analysis given minimal architectural design input and outputs the same detailed BIM data with much smaller input values than alternative BIM applications such as Revit [18]. This program makes it simple to acquire conceptual design models and precise cost estimates, enabling value analysis of various conceptual design alternatives based on a variety of construction building specifications and related cost estimates. DProfiler does not support complex or free-form building shapes and is limited to simple orthogonal building shapes. Moreover, DProfiler is mainly used for the economic evaluation of construction projects and lacks more favorable interfaces to connect with other BIM software. This is the reason why DProfiler is not common in the European market [19]. Missing architectural elements and missing information on geometric parts of the BIM model can result in an incomplete bill of quantities, which can lead to incomplete LCA results.

One of the two most widely used BIM design programs is called ArchiCAD, which was created by the American company Graphisoft and is IFC-certified by buildingSMART. The program can do budget calculations by entering the unit cost of materials and supplies, extract all quantitative data, and export it to an Excel file, as well as allow the user to enter a precise number for the carbon footprint per kilogram of each resource. Calculating carbon emissions in $kgCO_2/kg$ differs from the commonly used SimPro $kgCO_2/m_2$ [20]. Therefore, it is not possible to automatically export the carbon footprint data to the LCA software. The files that Archicad produces demonstrate good convergence of the measured values. Moreover, the reference building may be positioned precisely due to ArchiCAD's compatibility with environmental settings and climatic data. This is one of the great tools in ArchiCAD that makes environmental simulations easier [21]. However, Archicad requires a complex process of removing existing doors present in the model, and compared to Revit, which does not require simplification, Archicad has limitations in the validation process [22]. Archicad model compression IFC files take longer to load, which reduces productivity and file conversion efficiency. Therefore, it is also possible to speed up the loading of Archicad models by removing the redundant parts of the data in the files through optimized compression tools such as IFCCompressor [23]. ArchiCAD still has a small limitation for custom parametric modeling functionality because of the use of the parametric programming language GDL, which requires a higher level of programming skills from the user compared to Revit's visualization of family components. ArchiCAD relies only on a separate plug-in, MEPModeler, for MEP, which lacks the ability to calculate ventilation and electrical loads, thus reducing the quality of the LCA.

Table 1. Three common BIM 3D modeling software associated with the LCA tool.

Name	Developer	Features	Limitations	References
Revit	Autodesk	1. 3D project visualization; with high data interactivity 2. Automatically quantifies and extracts the number of construction materials in a building project without manual data input 3. Low application costs 4. Real-time information updates	1. Probably not compatible with Russian code projects, only supports Windows system 2. Poor functional selection of processing specifications 3. Time-consuming and complex model building, limited capability for complex modeling 4. Need complete family data, no built-in more general design tools	[24–27]
Dprofiler	The Beck Group	1. Suitable for presenting models with an approximate level of detail 2. Rapid evaluation of design solutions; doing an economic evaluation of projects 3. Simple structure	1. Limitations in the range of geometric forms created	[15,18]
ArchiCAD	Graphisoft	1. Easy to use and strong collaborative integration 2. Can create quality construction drawings	1. Carbon emission units are different from LCA 2. Modify complex models 3. Extended loading time for compressed Industry Foundation Classes (IFC) files	[20,22,23]

3.2. LCA Tools

LCA is a technique created to measure the environmental impact of a product by accounting for every stage of its life cycle, including the extraction of raw materials, manufacturing, and transportation to the site of use, construction, operation, and maintenance, as well as end-of-life and recycling [28]. According to ISO 14040-14044, LCA is described as the collection and evaluation of a system's inputs, outputs, and possible environmental effects over the course of its whole life cycle [2]. This evaluation method is a complex and time-consuming project, and there are also problems with software interoperability, calculation methods, and database compatibility. As shown in Table 2, the tool characteristics and limitations of LCA tools applicable to integrated BIM software are demonstrated.

Table 2. Features and limitations of the LCA tool.

LCA Software	Region	Features and Benefits	Limitations	Website	References
SimaPro	Netherlands	1. More systematic way of modeling and analysis 2. Highly user-friendly; can add new parameters, support, and functional equations 3. Clear and accurate display of results 4. Optional LCI database	1. Calculation requires manual extraction of parameters such as impact factors	https://simapro.com/ (accessed on 7 February 2023)	[29,30]
openLCA	Germany	1. Free and open source 2. Compatible with most databases and LCIA methods	1. Only for users with Java expertise 2. Open source may bring errors to the software 3. Results cannot be refreshed automatically 4. The chart is rough	https://www.openlca.org/ (accessed on 7 February 2023)	[29,31,32]
Tally	United States	1. Providing effective and fast LCA feedback 2. More user friendly 3. Quantify the environmental impact of construction materials	1. Need to identify the modeled material correctly 2. Need to import similar information for the same material in each new analysis 3. Geographic sources are only available for the US region	https://www.choosetally.com/ (accessed on 7 February 2023)	[8,33,34]
GaBi	Germany	1. Inclusive of all building life cycle processes 2. Unrestricted editing and high flexibility	1. Limited range of architectural applications	https://sphera.com/product-sustainability-life cycle-assessment-lca-software/ (accessed on 7 February 2023)	[35]
Umberto NXT	Germany	1. Link Microsoft Excel cell values to the Umberto model; visual graphs to show LCA results 2. Automatic update of cell values when they are changed, and the possibility of modifying relevant parameters 3. Possibility to create separate interfaces with SAP or systems	1. More complex 2. Does not provide any additional functions	https://www.umberto.de (accessed on 7 February 2023)	[29,36]

Table 2. *Cont.*

LCA Software	Region	Features and Benefits	Limitations	Website	References
Athena EcoCalculator	Canada	1. Free to use, very intuitive, and fast 2. Regionalized and available for new and retrofit projects.	1. Predefined technical configuration, not editable 2. No sensitivity analysis was provided 3. Parameters such as impact factors need to be extracted manually during calculation 4. Lack of consideration of the thickness of building elements 5. Cannot change the LCI data source	http://www.athenasmi.org/our-software-data/ecocalculator/ (accessed on 7 February 2023)	[37–39]
ATHENA Impact Estimator	Canada	1. Free to use, more flexible, and accurate 2. Output building different life cycle body environmental impact	1. Time-consuming manual input of bill of materials 2. Higher risk of missing elements and errors	https://calculatelca.com/software/impact-estimator/ (accessed on 7 February 2023)	[40–42]
BEES	United States	1. Multi-dimensional life cycle is adopted for a more comprehensive assessment	1. A lack of information specific to construction 2. Failure to record variations in emissions caused by various building methods 3. The data include a lot of uncertainty	https://www.nist.gov/services-resources/software/bees (accessed on 7 February 2023)	[43,44]

SimaPro, created for integrated waste management, life cycle analysis, carbon and water footprinting, product design, development of environmental product claims, identification of key performance indicators, and sustainability reporting, is the LCA analysis tool that receives the highest usage [45]. SimaPro may significantly reduce the amount of time needed for life cycle analysis. SimPro has greater flexibility and simplicity than Gabi, allowing unrestricted editing and access to LCI databases [46,47]. SimaPro currently lacks the ability to model a range of different suppliers in the LCI dataset, and connectivity between different products remains a functional module that needs to be developed. Also, due to the differences between the various BIM plug-in tools, the results of LCA calculations using Simapro cannot be directly correlated with the results of the BIM energy and carbon assessment plug-ins.

The openLCA tool, with good user-friendliness and support for original databases, can build graphical models automatically or manually. The validity of LCA findings frequently depends on the referenced database because open source is free. Because the user must manually enter the data into the database, there is no convenience [48,49]. Moreover, the time-consuming calculation makes the software correspondingly slow compared to SimaPro. Applications based on specialized LCA tools such as SimaPro and openLCA do not assess the material usage of the building process, limiting the reliability of LCA results. Manually created modules reduce the efficiency of interacting with BIM information and have the potential for data errors.

Tally is another Revit plug-in application that can be used to facilitate alphanumeric and graphical data exchange, extracting building materials inventory data and evaluating the full set of U.S. EPA TRACI environmental impact categories associated with the entire life cycle of building materials (extraction and material manufacturing to use and end-of-life) [50]. Tally makes it easier to determine the environmental effect of various building materials for use in the comparative study of various design alternatives and overall building analysis. Additionally, Tally may be directly connected to the Gabi database and read data about the number of materials from the BIM model. Compared to Athena software, this has a benefit [51]. However, because it is not possible to model LCA data directly for anything other than the goods included in the database, LCA reporting is not as reliable [52]. Moreover, Tally and Athena were unable to identify the materials selected for the Revit project, their database was inflexible and insufficient due to the lack of different materials, and thus, the inability to edit the material information made it difficult to validate the accuracy of the project's LCA analyses. Tally mostly had to do with the accessibility of environmental data because there weren't many constructive alternatives in the plugin's database, necessitating assumptions about the most comparable kinds of building components that might be conjectured.

The efficient Umberto NXT provides users with easy-to-understand flowcharts and sankey diagrams to help them quickly access results. With the use of several midpoint and endpoint selection categories, Umberto NXT's graphical modeling analyzes, records, and visualizes environmental consequences in order to determine the environmental impact of goods [53,54]. With Umberto NXT's user-friendly interface, automated calculations, and integrated features, companies can improve overall efficiency. The Umberto NXT is also popular with users for its more sophisticated software performance, despite not being able to offer any additional features [36]. In contrast to other software, Umberto NXT is not online software and requires more experienced LCA specialists to apply it to BIM software, requiring additional streamlining work to make it available to AEC industry professionals.

Athena Impact Estimator and Athena EcoCalculator are free LCA tools developed by the Athena Institute [55]. The Athena EcoCalculator could be used to calculate a building's carbon footprint and show the results in spreadsheet format. Based on a small number of inputs, the program calculates a building's environmental effect. The LCI data sources cannot be modified, nor does it offer sensitivity analysis to demonstrate changes in the environmental effect of building components over a variety of design choices. The BIM interoperability advantage of Athena Impact Estimator over Athena EcoCalculator is the ability to link CAD programs to import bills of materials [37]. However, the Athena Impact Estimator also has a high probability of missing elements and erroneous results [41].

Additionally, there is a constrained number of LCI cell processes available when utilizing the Athena and Tally tools since users cannot alter the data source or specifics. In contrast, SimaPro has the advantage of manually selecting LCI unit processes in this regard [46]. Different software tools are used to perform LCAs, and the results may vary depending on the software selected by the user. Different LCA software takes different applications, databases, and implementation scopes, resulting in differences in calculating environmental impact factors. For Brazilian particleboard, Lopes Silva, Nunes [56] compared the environmental impact findings using SimaPro, Gabi, Umberto, and openLCA. They discovered that due to discrepancies in the background database, access to the import process was restricted or the import failed. Additionally, the versions of the standards that each piece of software uses contribute to the variations in the environmental effect outcomes [57]. Al-Ghamdi and Bilec [46] conducted research showing a 10% difference in global warming for Athena Impact Estimator, Tally, and SimaPro.

3.3. Energy Consumption Tool Compatibility

Building energy modeling is essential for a variety of purposes, including setting baselines and managing building energy. Predicting building energy consumption is a complex task due to the presence of multiple variables, which makes it impossible to complete calculations accurately. The operation of energy consumption software connects BIM models and LCA tools to enable modeling that accurately predicts energy consumption and provides data for further environmental impact analysis [58]. The data interoperability between the energy consumption tool and BIM plays a key role. Table 3 lists the data exchange formats, application features, and limitations of common energy consumption tools.

Table 3. Common energy consumption tool features and limitations.

Energy Consumption Tools	Applications	Data Input Format	Data Output Format	Advantages	Limitations	References
Designbuilder	Cooling and thermal lighting loads; electricity; ventilation consumption	gbXML; .pdf; .bmp; .jpg; .png; .gif; .tiff; .dxf	Auto CAD; .xsl; .ddb; .IDF;	Save modeling time; good geometry model export; user-friendly	Manually modify the default values according to the actual plan needs	[59–61]
Green Building Studio	Electricity energy calculation; carbon emissions; lighting analysis; cost analysis	gbXML; 3D CAD	gbXML; VRML	Multiple simulations can be performed without reverting to the original geometry model; additional method runs can be added	It is easy to cause the software to simulate according to the default value and ignore the export error and simulate	[62–64]
IES-VE	Daylight; ventilation; thermal analysis; HVAC system simulation; geometry editing	gbXML; .dwg; .dxf	.ve	Provides a simplified approach to building geometry and its design parameters; allows for bidirectional information flow	Requires software for linking between BIM and LCA; no educational free version available for analysis	[65]
Autodesk Ecotect	Cooling and heating loads; energy design; lighting performance; acoustic environment.	gbXML; XML; IFC; DXF; Imagine; Lightscape; Maya; Reanimation; Renderware; .dxf; .iff	Auto CAD; .dfx; EnergyPlus; etc.	Easy to use; automatic generation of charts; export of results as animations	Excessive runtime; complex simulation engine non-compliant	[64,66,67]
eQUEST	Shading design and analysis; cooling and heating loads; energy consumption simulation	DWG; gbXML; IFC; DOE-2	gbXML; .dxf; .xls;	Free; allows estimation of energy costs and lighting; editable default parameters and interactive graphics	Too long runtime; energy output after DWG import only supports 2D level; cannot simulate ventilation and thermal comfort	[65,68]

The Designbuilder program is the first full user interface for the EnergyPlus dynamic thermal simulation engine and has the ability to create graphics at any stage and rapidly provide precise environmental performance data [69]. Designbuilder obtains the BIM model through gbXML. The geometric model is exported by Designbuilder with good results. However, due to the default value of the software settings needing to be manually modified according to the specific plan [61], the import of geometric models from BIM software into energy simulation tools using gbXML, one of the most used data formats for information sharing, could save a lot of time by removing the need to generate building geometry in the simulation interface [70].

The web-based Green Building Studio (GBS) energy analysis tool performs energy simulation analysis for free and with fast graphical feedback [71]. The advantage of GBS is that additional scenario simulations can be added alongside the regular calculations [64]. GBS for end users is very user-friendly and does not require users to have computer programming or energy analysis experience, which increases the effectiveness of usage. However, the automated application of the tool may also lead to erroneous simulation results according to default values [63].

An integrated building simulation tool called Integrated Environmental Solutions®—Virtual Environment (IES-VE) gives customers access to several applications via a single data model. IES-VE is a platform for modeling building-related energy, daylight, renewable energy systems, and airflow performance [72]. The two-way information flow and the simplification of the geometric data parameters of the building model give great ease, even though the application is not well-liked by users since it demands money [65].

Autodesk Ecotect must receive Revit output as a complete file, and XML or gbXML are the types of format Ecotect can accept [67]. gbXML is more versatile and user-friendly than IFC and makes it easier to transmit building information across modern architectural design tools and other engineering analysis software programs [71]. Local weather data can be loaded in Ecotect, and energy simulations are performed for different design conditions. Further, under the building's defined geometry, material qualities, and regional weather, the cooling and heating loads of the area are simulated for the building's operating phase, confirming the correctness of the calculation findings [73]. Ecotect can present the results in colorful graphs and even increase the readability and convenience of the results through animations. However, the energy analysis program takes too long to run, and the complex simulation engine does not meet specifications and regulations [66].

A variety of users can benefit from the reasonably user-friendly and totally free energy analysis program known as eQUEST [74,75]. Using approaches for graphical display that are information-rich, the tool enables comparisons between various simulation situations. Given only a limited amount of architectural design input, it delivers thorough feedback on material amounts and energy analyses [76]. It also enables energy cost estimation, lighting system and daylighting management, and analysis of energy-saving strategies [65]. eQUEST runs too long and does not simulate natural ventilation and thermal comfort. Also, eQUEST imported via DWG only outputs 2D building-level energy data [77].

3.4. Integration Framework Methodology and Integration Process

According to the latest BIM-LCA integration method described [78], the main methods of BIM software integration with LCA tools are divided into five types (Figure 3): (1) bill of quantities (BOQ) import; the list of quantities of construction materials automatically generated by BIM software is imported into LCA for calculation. Glodon was used by Su, Wang [79] to export the BOQ, which is a process for transforming the component geometry data extracted from the BIM model into material and energy consumption data. This information is then input into the building environmental performance analysis system for analysis. Hollberg, Genova [9] composed the BOQ from the area and volume of building components automatically generated from BIM software and, after completing the calculation process with LCA factors in Dynamo, connected the BIM model in the form of XLS and visualization on the model with colors. It helps to improve the problem of inefficient data exchange mechanisms between BIM and LCA tools. (2) IFC import; IFC is another data exchange format that exports BIM data as an IFC model. The necessary data is extracted, reconstructed, and integrated into the LCA template using the developed data transfer tool [80]. Xu, Teng [80] exported the model of a 30-story residential building in Hong Kong in IFC format to SimaPro software, which enables automatic data mapping. Alwan and Ilhan Jones [81] also confirmed that the IFC contains implicit carbon data well used for the information interaction between ArchiCAD and LCA software. (3) Using the BIM viewer; BIM based on the intermediate process viewer is used to view the list of LCA summary files in the model file exported by BIM software; through this LCA file, what is considered as building components is transferred to LCA software for analysis and calculation. This method maintains an in-depth LCA study in a specialized LCA environment while allowing the attributes of LCA profiles to occur in 3D in the environment. (4) Using the BIM plug-in to calculate LCA directly; the BIM plug-in is able to obtain the LCA database and record LCA information directly on the BIM model in the building components. This approach, nevertheless, also takes a lot of time and work. Santos, Costa [51] found that the Tally plug-in tool eliminates the need to export BOQ and allows viewing and reading building component information directly in the BIM model. This plug-in for the BIM environment may be connected to a third-party LCA database to fully utilize BIM's capabilities as a data store and visualization platform for quick BIM-LCA integration. (5) LCA plug-in calculation; LCA plug-in calculation is a common integration method through LCA plug-ins (such as Dynamo) in the BIM environment to directly calculate the LCA environmental impact of BIM components. Ansah, Chen [82] completed LCA calculations in Revit using the built-in calculation tool Dynamo plug-in and wrote the impact assessment data into the BIM model. This embedded visual programming tool can provide unlimited nodes, thus facilitating more customized computational tasks. Furthermore, optimizing the node code using Python technology reduces the running time.

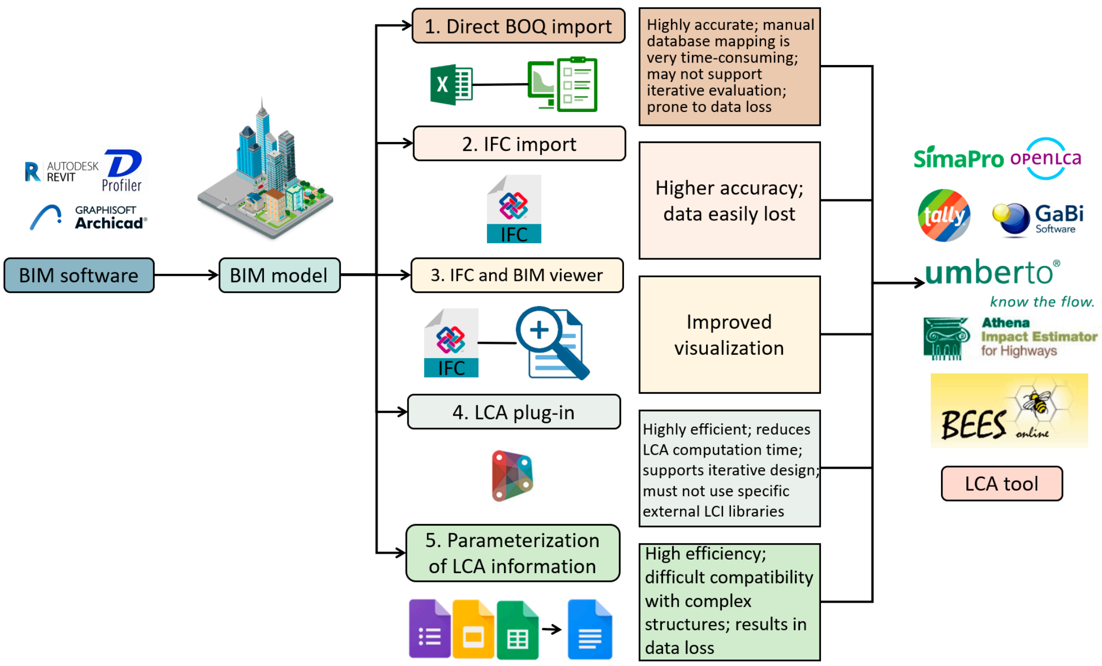

Figure 3. BIM process integrated with LCA approach framework.

Zheng, Hussain [83] compared BOQ-based, parametric tool, BIM–LCA plug-in, and IFC viewer respectively with manual LCA calculations and found that the GWP results varied by −0.54%, −1.09%, 1.33%, and −0.82%, respectively. Although the BoQ method significantly reduces the effort of data collection, errors may occur because the information is only indirectly linked. Also, the manual database mapping of the BoQ method is very time-consuming and may not support iterative evaluation. In addition, information is usually not fed back to the modeler, and decision support is lacking [84]. In this study, the BOQ- and IFC-based methods are close to the results generated by manual calculations; the method of automatic reading of the IFC of the structure leads to errors in the number of building objects, risks the loss of geometrical data, which affects its accuracy, and lacks flexibility and standardization [85]. Additionally, BIM viewers enhance the visualization of LCI libraries by viewing and exploring BIM models in 3D. Open BIM data formats and model-based LCA visualizations (including color-coded IFC model viewers) are widely accepted and demanded, but the acceptance of uncertainty visualizations is low, which requires further research [86]. It may be inferred by watching the computations and examining the BOQ that fluctuations in the quantity of material and streamlined calculating procedures are the causes of outcome variances. Given the variety of methods available, the ontological and semantic standards of the data must receive more consideration [87]. Kim, Kim [88] used parametric algorithms to automatically generate BIM models from 3D point clouds with an error rate of 1.4%. However, in terms of efficiency, the BIM–LCA plug-in and parameterized tool approaches greatly reduce the time to define, select, and match LCI datasets by 60-fold and 6-fold, respectively, compared to the direct extraction BOQ approach [83]. LCI development and LCA calculation times are significantly reduced when using plug-ins compared to other methods. Plug-in methods that support an iterative design process performed entirely within the BIM environment may not use specific external LCIs, but only the tool's material database. The LCA information parameterization method can be linked to the BIM model at any point in the building design process, and the great flexibility increases the potential for real-time LCA. Mowafy, El Zayat [89] integrated the use of Autodesk Revit and Grasshopper for parametric analysis to create rich BIM models. Optimization of recycling methods through parametric scripts provides reuse percentages and likelihoods and their impacts on operational and implied emissions, which can help in the development of reuse and recycling policies. However, the LCA information parameterization approach skipping the quantity control phase may lead to significant differences in BOQ. Mapping linked data through explicit structures helps to simplify the data structure of scripts and promotes readability of the code visible in the parameterization tool [90]. Thus, the parameterized tool, despite running at a moderate level of accuracy and efficiency, is prone to crashing and lagging due to its high memory requirements.

3.5. BIM-Integrated LCA Application

BIM models may offer building information and enable operational simulations, and they considerably improve data accessibility and streamline the LCA data-gathering process. The most popular technique at the moment is to extract bills of materials using BIM and connect them to external databases. Table 4 shows recent examples of integrating BIM and LCA, highlighting the features of the integrated approach.

Table 4. BIM software integration LCA tool application case.

BIM Model	LCA Method			BIM Software	LCA Tool	Energy Consumption Calculation	LOD	Environmental Impact Indicators	Integration Method	Integrated Features	References
	Functional Unit	Lifespan	Database								
A road section on the European Route 6 (E6) between Arnkern and Moelv, Norway	A road	-	Norwegian EFFEKT model version 6.6, EcoInvent 3	Autodesk Civil 3D	SimaPro Dynamic Link Library	-	-	Global Warming Potential and Cumulative Energy Demand	- LCA plug-in calculation	1. Evaluate CO_2 emission results more accurately (3.7% higher) 2. Limited range of LCA evaluation results	[91]
Multi-family house in Huai'an City, Jiangsu Province, China	The whole building	50 years	Chinese reference life cycle database	Autodesk Revit	Building Environmental Performance Analysis System	GBS	LOD 300	Global Warming Potential, acidification, eutrophication, and suspended air particles	BoQ exports from BIM environments to Glodon BOQ to integrate tools	1. The need to modify the BIM design in different construction phases raises the cost 2. Manually matching material data between BIM and LCA tools 3. Quantifying the dynamic environmental impact results of the building	[79]
Prefabricated residential buildings in Hong Kong	The whole building	50 years	Ecoinvent database v.3.5	Autodesk Revit	Dynamo	-	-	Global Warming Potential and Cumulative Energy Demand	LCA calculations in BIM using the plug-in Dynamo tool	1. Automated system results 2. Ability to provide LCA results for different ratings 3. No better coordination in terms of structural elements in modeling	[82]
Chuzhou Hospital Building, Anhui Province	Hospital Building	-	China building carbon emission factor Database	Autodesk Revit2017; GTJ2018	-	GBS	LOD 300	Global Warming Potential	BoQ exports from BIM environments to Glondon GTJ2018 to integrate tools	1. Automatic data entry speeds up the creation of LCA models 2. Secondary modeling consumes a lot of time. 3. Compatibility issues between different BIM software 4. Lack of carbon emission factor database and lack of characterization	[23]
Three-story extension to the Basler & Hoffmann Engineering office building in Esslingen, Switzerland	Architectural elements, such as walls or windows	50 years	Ecoinvent V2.2	Autodesk Revit	Dynamo	-	LOD 300	Only the GWP was analyzed	BoQ exports from BIM to Dynamo tools to integrate LCA	1. Material ID needs to be manually connected with the LCA database and BIM elements 2. The color visualization of the exported results by Dynamo calculation in BIM 3. The quality of LCA results is not guaranteed	[9]
Typical multi-story office building in Brazil	The whole building	-	Ecoinvent v3.1	Autodesk Revit	open LCA 1.5.0	GBS	-	Human health, ecosystem quality, resources depletion, and climate change	BoQ export from BIM to LCA software	1. Streamlines the data collection process for buildings and provides comprehensive feedback on projects. 2. LCA study does not specify the performance of building materials throughout their full lifetime and must be supplemented with other information 3. Autodesk Revit uses the GBS application as a smart energy setup that requires precise filling of different assumptions and parameters	[92]

Table 4. *Cont.*

BIM Model	LCA Method			BIM Software	LCA Tool	Energy Consumption Calculation	LOD	Environmental Impact Indicators	Integration Method	Integrated Features	References
	Functional Unit	Lifespan	Database								
A museum in Guangdong, China	Hospital Building	50 years	-	Revit	-	Designbuilder	-	Greenhouse Gas Emissions	Import BOQ to LCA software	1. It can reduce the amount of time needed for modeling 2. Complete economic and energy consumption simulation analysis is possible 3. Revit and Designbuilder have incompatibility issues	[60]
Netherlands Office Building	An office building	50 years	Ecoinvent	Revit	Tally ATHENA Impact Estimator	-	-	TRACI 2.1 Indicator Set	Read BIM material data via Tally plug-in BoQ exports from BIM to ATHENA Impact Estimator tool to integrate LCA	1. ATHENA and Tally export BOQ in a BIM-based environment 2. Allowing users to contribute or change effect information is not allowed in materials. 3. Neither addresses life cycle costs of projects	[51]
Brazilian interior walls	1 m^2 interior walls	-	Ecoinvent	ArchiCAD	SimaPro	-	-	Global Warming Potential	BoQ export from BIM to Excel tool to integrate Excel tool to integrate LCA	ArchiCAD automatically extracts carbon footprint data without SimaPro extraction	[16]
Ghana Single-Story Residence	180.50 m^2 Residence	50 years	The Inventory of Carbon and Energy database V2.0	Revit	-	IES-VE	-	Global Warming Potential; Cumulative Energy Demand		-	[72]
An assembly-type residential building in Hong Kong	30-story building	-	-	Revit	SimaPro	-	-	Embodied carbon	IFC import to LCA	Accelerated LCA modeling with 91.5% improvement in efficiency	[80]
One residential building in the UK	2-story residential building		proxy database (ICE V2.0 or V3.0)	ArchiCAD	pycab	-	-	Embodied carbon	IFC import to LCA	IFC format and BIM software information interaction will make it easier for practitioners to assess carbon at an early stage to improve design decisions and evaluation	[81]
A residential building in Quebec, Canada	A residential building	60 years	Ecoinvent v3.3	Revit	openLCA	-	LOD 100/LOD 300	Human health, ecosystem quality, climate change, and resources	BoQ Export from BIM to Excel tool to integrate LCA	LOD 300 is better suited to calculate climate change and resource use aspects	[93]
Clinic building	Whole clinic	60 years	Ecoinvent 3.4	Revit	openLCA 1.9	EnergyPlus; Honeybee	-	Global warming potential values; implied carbon analysis	Integration of LCA information directly into LCA	Honeybee requires users to manually identify zones, spaces, buildings, HVAC, and schedules	[94]

Table 4. *Cont.*

BIM Model	LCA Method			BIM Software	LCA Tool	Energy Consumption Calculation	LOD	Environmental Impact Indicators	Integration Method	Integrated Features	References
	Functional Unit	Lifespan	Database								
A multi-story residential building in Brazil	A building	30 years	GaBi 6	Revit	Tally	GBS	-	TRACI 2.1 Indicator Set	Read BIM material data via Tally plug-in	Tally requires separate consideration of standard designs to construct reliable analysis results	[95]
A multi-family house in Tirupati, India	A residential building	100 years	Express Publisher Document database	Revit	One Click LCA	-	-	Global warming potential; acidification potential; eutrophication; lower atmospheric ozone formation	BIM export BOQ to LCA tool for calculation	LCA has not developed a detailed cost analysis for the use of alternative materials	[96]
Single-family social housing in Maranhão, Brazil	1 m^2 of the non-structural shell	40 years	GaBi 4.4; Ecoinvent	Revit	Dynamo	-	-	TRACI 2.1 Indicator Set	Inserting LCA data information into the BIM model	Visual programming creates links that allow spreadsheets to link LCA information on BIM elements	[97]
2-story building in Philadelphia, Pennsylvania	One building	60 years	GaBi	Revit	Tally	-	-	Acidification potential, eutrophication potential, global warming potential, ozone depletion potential, smog formation potential, and non-renewable energy demand	LCA plug-in calculation	-	[98]
Melbourne Detached Homes	A single-story brick veneer house	60 years	-	Revit	Tally	FirstRate5	-	acidification potential; eutrophication potential; global warming potential; ozone depletion potential; smog formation potential	LCA plug-in calculation		[99]

Comprehensive assessment and visualization of BIM can simplify the LCA process by providing a complete list of components in the early design phase, reducing the cost of changes needed in later stages [100]. BIM and LCA work together to save computation time for the intricate LCA process and increase building efficiency and resilience by identifying mistakes early in the design phase so they can be remedied [33]. Xu, Teng [80] significantly improved the efficiency of building life cycle assessment by exporting IFC files from the Revit model of a residential building in Hong Kong and transferring them to SimaPro for computing, which accelerated the generation time of LCA results by 91.5%. Ansah, Chen [82] used Dynamo plug-in to support Python and C# technology to link with the Revit database, quantified materials, and extracted data to generate Excel tables, and improved calculation efficiency using script tracking execution to quickly retrieve errors in the BIM model.

Enhancing LCA integration into BIM can help buildings function more sustainably [101]. The BIM software simulates the energy consumption of different building materials. It represents the LCA results in an optimized digital model, which facilitates the reduction of energy consumption (annual energy application intensity: 45%) and environmental pollution (acidification potential: 33.11%; global warming potential: 35.33%) [95]. With the recommendation of the BIM-integrated LCA framework, Wang, Wu [102] found a 45% reduction in carbon emissions from demolition waste recycling of residential buildings. LCA tools link energy consumption software and BIM software to identify optimal optimization solutions for energy and environmental emissions, and the optimization is evident in design decisions. For example, the integrated approach applied to a 2-story building in Philadelphia, Pennsylvania, reduced the environmental impact of the TRACI 2.1 category by 53–75% compared to traditional environmental calculation methods. The new construction solution implemented allowed the structure and envelope to be recycled, demonstrating economic benefits and environmental sustainability [98]. Engineers may develop computerized models to increase the sustainability of construction through assessments based on sustainable concrete structures by using the BIM-LCA-AHP technique, as demonstrated by Abdelaal, Seif [103] Tushar, Bhuiyan [99] verified that Revit integration of FirstRate5 energy tools and Tally tools could provide environmentally friendly, energy-efficient design solutions that provide a significant contribution to reducing the carbon footprint and energy consumption of a house. It is difficult to achieve sustainability in the first stages of building construction because the integration of sustainability principles in BIM is ambiguous. Furthermore, BIM still makes it challenging to access integrated idea-mapping elements [104].

The analysis of LCC is also an important factor to be considered in the design phase of users. The creation of integration tools makes it easier to semantically enhance BIM models and increases how well BIM is integrated with LCA and LCC. For the LCA assessment of a 250 m high tower in Rabat, Santos, Aguiar Costa [105] developed the BIM for Environmental and Economic Life Cycle Assessment (BIMEELCA) tool, which not only ensures the user's success in adding new information to the model itself but also enables the environmental assessment to be carried out in a low LOD (200) building model. Additionally, BIMEELCA enables users to add more data pieces to expand the BIM model building as a data silo, supporting automated simulation in the design and operation phases and contributing to the decision-making process [51]. However, the BIMEELCA tool has some drawbacks: the need to add new types of shared parameters manually, and the inability to obtain the number of material applicability times.

4. Integration Tool Impact Factors Analysis Improvement

4.1. Level of Development

Architects, engineers, and construction professionals may specify and explain the content and dependability of BIM in a highly visible form at various phases thanks to the level of development (LOD) [87]. BIM objects may vary in their amount of detail or development in relation to the wealth of geometric and non-geometric information they give in a BIM model [106]. As seen in Figure 4, which displays the building elements of the BIM model under LOD 100–LOD 500, the higher the LOD level, the more detailed the information of the BIM object.

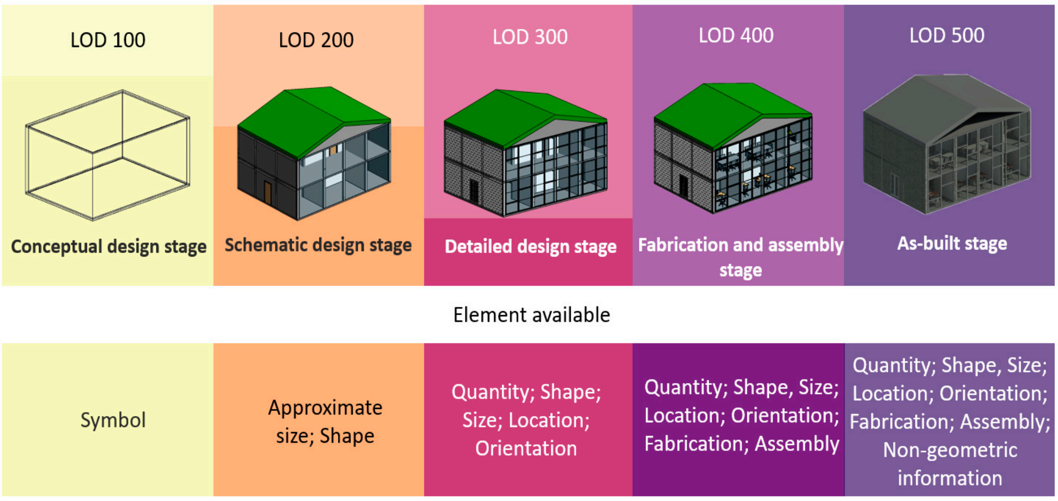

Figure 4. Building elements in the BIM model under LOD 100-LOD 500.

Accurate LCA calculations and building modeling will be impacted by the absence of a standard and well-defined concept for LOD. In order to successfully address the absence of requirements information in a project, LODs enable the specification of exact content requirements for BIM model parts within a set period [107]. LCA databases must provide environmental consequences at various levels of granularity to support varying LoDs. This allows the approach to be applied to support and finance project choices throughout the development phase [108]. The LOD 100 model is created in the conceptual design phase through generic symbols or graphics, while the type of elements is unknown. The LOD 200 building elements have an approximate number of LOD 100, and the BIM model under this schematic phase contains the base model elements [100]. Röck, Hollberg [100] used the LOD 200 model to meet the understanding of LCA from early BIM models. The high-level model, however, makes LCA results more reliable. As a result, the LOD is linked to a database of inventory-building components that can be utilized for material calculations and is improved during the design process. LOD 100 and LOD 200 enable designers to promptly evaluate and adjust early design decisions [108]. However, the unavailability of details of the production process and quantities of building materials does not allow better decisions to be made in the concept phase to reduce environmental impacts. Therefore, more robust decisions are deferred to the detailed stage. The BOQ technique provides information commensurate with the low LOD that defines the first BIM model while expediting a streamlined LCA procedure in the early design phase. At LOD 100–200, decision support is more effectively provided by simplified design tools that only need a small number of design inputs to anticipate quantities and compute material quantities, accelerating LCA in the early design phase. The simplified Active House-LCA tool developed by Di Santo, Guante Henriquez [109] was combined with BIM to quickly make early decision criteria for sustainable building design under the Casa Zappa LOD200 model, but there are limitations in economic assessment. Low or average information in the BIM model can lead to biased results, and the high LOD cannot be extracted and utilized [90].

Objects at LOD 300 will have exact geometry and particular data, and LOD 300 allows the number, shape, size, position, and orientation of architectural elements to be accurately displayed [110]. Rezaei, Bulle [93] compared the LCA calculations of LOD 100 and LOD 300 models. LOD 100 is suitable for determining the uncertainty of materials in components in the early design phase. In contrast, the detailed design phase requires a more refined

LOD 300 model to calculate the environmental impact of different building components, thus making the detailed data of BIM more applicable in the LCA. The detailed data of BIM in LCA is more applicable. LOD 300 was often chosen as the model development level for the case study because that detailed design phase is the phase where important decisions are made, so LOD 300 is also determined to be the most appropriate for LCA analysis. Instead of arbitrarily choosing a higher LOD, the BIM model should qualify the necessary LOD to allow for the direct and correct extraction of important information [111]. LOD 400 is the fabrication and assembly phase that adds complete fabrication, assembly, and detail information to LOD 300 [112]. Compared to LOD 500, which has the highest level of detail, LOD 400 provides quick access to critical information and has detailed graphical information and additional non-graphical information.

However, the complexity of performing building services LCI in different LODs of BIM models makes the data calculation of LCA more difficult [113]. Su, Li [114] assessed that the LOD of the BIM model influences the management of demolition waste, and the lack of design details of the BIM model at lower LODs makes the final impact results deviate from the actual results. Because the LOD of BIM cannot match the difficulties of the adopted database standard, it is particularly important to reconfigure the existing LCA database to distinguish between models with different levels of LOD [115]. Dupuis, April [116] propose a methodological structure in which the LOD100BIM model can automatically perform LCA calculations, and the new data layers and data formats facilitate BIM models with different development levels to be able to be automatically computed by LCA and reduce the uncertainty of the model.

4.2. Degree of Automation

During the integration process of BIM software and LCA tools, data linking in the interaction of different software, if it requires manual process, will make the iterative design process difficult, and manual operation for some databases and data selection is a very common method. The application of BIM and LCA automatic/semi-automatic integration is beneficial to improve the evaluation's efficiency and enhance the future usability for more complex models. Semi-automation occurs automatically by sharing and providing information, but importing and exporting data requires some manual transactions, and improved scripting facilitates the linking of multiple platforms as a basis for building new LCA programs or plug-ins. However, as more data is processed, additional required details are not available in the BIM system. Completely automated information transfer is fully automated, integrating multiple platforms to build scripts, but may be limited to preliminary information due to data changes and scenarios that do not reset the framework within the LCA study [117].

Jalaei, Guest [94] used a semi-automated mechanism for energy analysis using Honeybee, which does not give maximum user-friendliness and requires the user to manually identify the area, space, and other parameters, which is a test for the user. Xu, Teng [80] utilized the BIMToSimaPro tool to automatically transfer BIM exported IFC data into SimaPro in CSV format for the study of residential buildings in Hong Kong, enabling automatic data mapping and reducing the LCA generation time from 729 min to 62 min, which greatly facilitates and brings convenience and efficiency to professionals conducting carbon assessments. Compared to Tally software's manual process of mapping materials, which may result in data errors and lack of quality, One Click LCA as a BIM plug-in enables automatic mapping of Revit components to materials, and the One Click LCA semi-automatic plug-in is used in the Indian residential carbon footprint estimation for faster, simpler, and more accurate results [118]. The semi-automated process allows the user to make changes to some material data and manual data entry to obtain uncertain analog inputs, which is more user-friendly than fully automated default settings. Soust-Verdaguer, Llatas [119] evaluated the assessment of a dwelling with timber and concrete masonry in Uruguay using a semi-automated method to automatically obtain the BOQ of materials in the BIM model and automatically link to the LCA spreadsheet, and to allow human modification of the BIM component data and the environmental impact results to vary automatically, enabling a semi-automated process that is more reliable, transparent and quality assuring.

Ansah, Chen [82] validated a fast real-time automated workflow to speed up the Dynamo evaluation process by automating the creation of parameters with system partitioning and setting them after populating the BIM with LCA data, thus improving the process of integrating the tool calculations. Full automation is simpler and easier but can result in incorrect output due to incorrectly set default values. Because full automation relies on default values set by the model system, it can lead to significant changes in simulation predictions and compromise the objectivity and reliability of the simulation output [120]. Serrano-Baena, Ruiz-Díaz [121] used the MLCAQ approach to provide a reliable method for automated multi-criteria comparison of building materials from an environmental point of view based on BIM, and this open-source methodology linking the IFC components with the Constructive Solutions Database will become a popular international resource. BIM3LCA has been developed to address the difficulty of automatically comparing alternative design solutions for different material choices, and real-time LCSA calculations are possible through native BIM software development [122]. Furthermore, the performance of the automatic matching of elements and materials from the BIM model to the knowledge database is improved using Natural Language Processing (NLP) in order to enrich the environmental metrics of commonly used elemental materials. This serves as the foundation for a fully automated calculation process of greenhouse gas emissions from new buildings [123]. This might fill in the current gaps in the automated process of manually adding LCA data information, hiding missing model layers, and improving BIM models. Low-carbon building design has been made easier and mistakes have been minimized by automating implied carbon calculations in BIM settings through the use of Dynamo's model in the LCA process [124]. This automated approach accelerates iterative design assessment, decreases mistakes, time, and effort, and improves early decision making.

4.3. Interoperability and Data Exchange

Data translation between BIM software, energy consumption tools, and LCA tools is made possible through interoperability, which also helps to enhance workflow by removing the need for manual data copying from previously developed applications [125]. In the BIM–LCA integration approach, (a) the LCA information is imported into the BIM software as an API interface, (b) the BIM software exports the IFC format for output to the LCA tool, and (c) the BIM data and LCA data are made to be integrated into Excel or a programming program format to export the BOQ, as shown in Figure 5.

The first method is importing information with LCA data into the BIM model through an application programming interface (API) [126]. The .NET framework underpins the Revit API, making it possible to create plug-ins using languages like C#, F#, or Visual Basic [127]. The API may also import external data to construct new elements, automate repetitive activities, extract project data to generate reports automatically and obtain model information for input into performance assessment tools [128]. APIs can remove data from an application and use the system that receives the data written by the application. APIs are developed to be very flexible, allowing the user to decide what information should be exported for a particular element [40]. Utkucu and Sözer [125] successfully linked directly to Revit through Dynamo using the API. Insight 360 and computational fluid dynamics simulation tools were combined with the Revit API to study energy performance and natural ventilation. Figure 5a illustrates the API approach to interact with tools in multiple domains, which greatly saves time and effort and easily enables data updates. The use of API to develop custom tools for real-time bi-directional data exchange between BIMs is a future research direction that facilitates the ultimate standardized BIM data exchange. However, LCA plug-ins and Revit plug-ins may not have access to the influence factors in the LCA database, which affects the accuracy of the calculation results [35]. This has an impact on how well data is mapped from LCA tools to BIM objects.

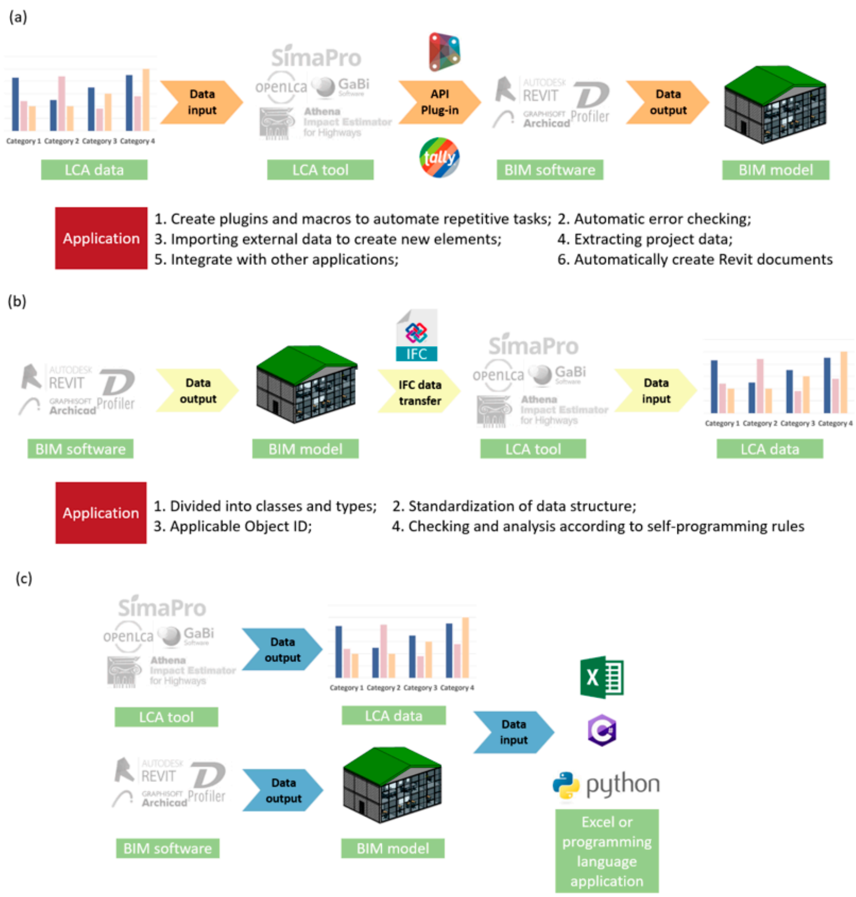

Figure 5. Three traditional methods of exchanging BIM software and LCA data. (**a**) API plug-in; (**b**) IFC data transfer; (**c**) Excel or programming language export.

The second method is to import BIM data into a professional LCA tool. A standard, open, and vendor-neutral data model for the built environment is called the IFC model [129]. By bypassing building material quantity calculations, practitioners may save time and become more productive thanks to the numerous case studies demonstrating the automated export of BOQ from BIM software as a means of transferring calculations in LCA software and the compatibility of the IFC format with BIM [130]. However, the different data structures of LCA and BIM make the application inefficient in the exchange mechanism and require manual mapping of material data. The IFC data exchange uses the object's ID [131]. As a result, updating LCA is made simpler because geometric and environmental data do not need to be rematched. It saves time and makes data access and analysis easier by reducing the number of times that data must be translated. However, data loss or change when converting models to IFC format is still a problem.

The third method is integrating data information from LCA and BIM into Excel or a third-party application developed by a programming program [132]. Kehily and Underwood [133] performed life cycle cost research based on components and materials by extracting quantitative data from BIM and linking it to an Excel file. The Excel-based approach is easy to follow and allows quick feedback, but it cannot handle complex cases effectively. In the case of highway integration in Norway, Slobodchikov, Lohne Bakke [91] used C# as the programming language in Microsoft Visual Studio to combine LCA data with the BIM model. In order to generate scripts that extract the final data for the overall impact of each construction choice in the model for the output worksheet, pre-defined nodes were connected into logical sequences that were not keyed into the programming language. This allowed for faster feedback than the IFC format. In order to automatically import LCA data into social housing BIM models and link them with Microsoft Excel spreadsheets, Bueno, Pereira [97] used visual programming. However, this data exchange approach is inefficient when dealing with complex calculations and is only suitable for basic simple LCA calculations [134].

5. Future Prospects

5.1. Dynamic BIM–LCA Method

Dynamic LCA is becoming a new future trend for advancing LCA research. Su, Wang [79] used a dynamic database consisting of temporal base flow, dynamic energy combination, and dynamic weighting factors as the primary assessment reference data for a multifamily dwelling in Jiangsu Province, China, over 50 years after its completion. The construction schedule was merged with the BIM model and exported to Excel, using the Glodon BOQ software and GBS energy calculation software to calculate dynamic environmental impact values, providing a new temporal perspective on environmental performance. DyPLCA is a newly developed dynamic LCA tool that includes a time database related to the construction supply chain, temporalizing the construction BOQ and providing a more realistic environment for performance [135]. However, the model does not cover all assessable impact categories, which is a major limitation in a comprehensive life cycle assessment. Mixed-use timber buildings in Switzerland provide a more accurate process-structured analysis of the BIM model with the help of dynamic LCA tools [115]. However, the presence of elemental components in the dynamic LCA database does not allow for obtaining a moderate parameter value and reduces the range of feasibility of the dynamic approach.

Continuous monitoring and recording of live information to create an Internet of Things (IoT) big data information platform for sub-regional buildings are beneficial to improve the efficiency assessment of dynamic LCA. In the future, there will be a great tendency to develop more user-interactive dynamic LCA, where the design optimization framework provides and updates dynamic material environment data with the latest and relevant data [136]. In addition, automated linking of BOQ and LCA databases is important for dynamic LCA [115].

5.2. Data Exchange Format and Method

BIM export, BOQ data format, and LCA export material information data format, used to link the two tools are often required to add manually. The automated transfer of information is currently worth developing. Automated data transfer optimizes the process of complex BIM integration with LCA to some extent, which brings great convenience to users while conducting complex software use and reduces the accuracy of output results to cope with multiple material types and complex construction activities. BIM software and LCA tools must be compatible with a common data structure to meet mutual data exchange [111]. Interoperability is achieved throughout the planning and design phase by using standardized formats for data sharing. This enables the spatial integration of LCA and BIM to incorporate environmental effect data into the entire data structure. Horn, Ebertshäuser [84] propose a bi-directional data integration strategy for IFC format in BIM and LCA, which is able to obtain continuous and understandable environmental impact throughout the dataflow process. Furthermore, information management systems include a variety of features to speed up the data interchange process [137]. Therefore, in order to make up for the lack of an automated procedure for enhancing LCA datasets to IFC materials and elements and to provide information about missing layers of imprecise model elements, Forth, Abualdenien [123] used an NLP-based approach to enrich models by automatically matching elements to LCA knowledge databases. The processing time of prototype implementations, which is prone to mistakes in manual operations, requires high NLP vector dimensions and accurate element classification.

5.3. Combination of Other Technologies

5.3.1. Semantic Web Technologies

Semantic Web technology enables effective management of BIM and LCA data in a common data format that helps computers to read the data directly [138]. The Semantic Web addresses the extensive manual input effort of earlier BIM–LCA integrations, simplifying the complex integration process and improving the accuracy of data integration. In order to build semantic knowledge bases and transform BIM data into a semantic web format for storage, semantic ontologies are established utilizing a framework [139]. The semantic web makes information more meaningful, reduces the time and complexity of accessing information, and has the collaborative nature of online systems, improving the effectiveness of LCA data computation. Sobhkhiz, Taghaddos [40] also confirmed that the proposed semantic web editing scheme applies to more complex BIM systems, but is challenging for user practice. Gui and Chen [140] conducted research on the integration of RFID technology into BIM models, in which Revit outputs IFC format in the form of output EXPRESS, and the RDF converted by the semantic web approach is queried by SPARQL to achieve automatic data capture, hence avoiding data mistakes and inconsistencies while entering data and changing information into the database system. This is the biggest advantage of integrating digital twin technology into BIM models.

Gao, Liu [141] developed the IFC IR ontology domain ontology to achieve a more effective online search for BIM information. However, BIM information has limited IFC ontology data, so more AEC ontologies need to be combined to populate a wider range of BIM resources. In summary, there is great space for enhancing semantic web technology for BIM and LCA. Nevertheless, there is not much research in this area, and the ontology database design of BIM information needs to be strengthened in the future. The optimized linking method of the semantic web also needs to be strengthened to improve user-friendliness.

5.3.2. GIS Technology

Su, Li [114] employed BIM to quantify the amount of construction waste, coupled with online GIS maps, to digitally store spatial data to identify the location of construction waste sites to plan travel routes. This reduces tedious manual data processing, quickly quantifies waste volumes, and assesses their impacts. GIS technology provides spatial data and analytical capabilities to quantify flows by location of service life, building material type, and quantity data [142]. Rahla Rabia, Sathish Kumar [143] simplified data extraction and sharing BIM technology for automation. Rapid assessment of energy-efficient hospital information in GIS tools for modeling and analyzing epidemic control activities can reduce COVID-19 propagation in the building life cycle. Furthermore, the integration of this technology needs to follow a standardized framework to filter and process accurate data from BIM models to ensure that unnecessary waste is reduced.

5.4. Construction Certification

Green certification of sustainable buildings is an assessment system to evaluate the environmental performance of buildings under official standards certification. Common building sustainability assessment methods are BREEAM (UK), LEED (USA), CASBEE (Japan), and BEPAC (Canada), as shown as the Table 5 [144]. Green supply chain management programs are credited by green building certification systems, which may be included in LCA to encourage sustainability throughout the entire life cycle. Green building certification systems assess the environmental impact of building materials [142].

Table 5. Characteristics and limitations of some green building certification systems.

Green Building (Location)	Green Building Certification System	Characteristics	Limitations	References
Apartment Building	G-SEED	Score based on the quantity of items under the Materials and Resources project group that were awarded the Green Label, Carbon Label, and Green Recycle Mark	Cannot quantify green building materials	[145,146]
Siemens Office Building, Switzerland	BREEAM	Grades are classified as Pass, Good, Very Good, Excellent, or Outstanding	Requires significant time and cost to obtain material information	[147]
	SBTool (Czech Republic)	Criteria are divided into environmental, economic, and social; the process includes pre-certification and final certification	LCA database mapping materials manually; time-consuming process; some elements missing	
A case study building	Leadership in Energy and Environmental Design (LEED)	-	Variability exists in regional considerations	[148]
School building structures and envelope systems (Canada)		Divided into three categories: Energy and Atmosphere; Materials and Resources; and LCA	LEED category needs to be modified to apply LCA assessment	[149]
Four-story residential complex (Canada)		Grades are classified as certified (26–32); silver (33–38); gold (39–51); platinum (52–70)	Accommodate different team members at different stages of the project delivery process	[150]

The green building certification system also has restrictions, and not all construction projects fall under its purview of examination. For instance, in G-SEED (Korea), the certification method only takes into account the amount of building materials that have earned the carbon label, the green recycling mark, or the assessment items relating to energy consumption throughout the usage phase [145]. Al-Ghamdi and Bilec [148] found significant differences in the results of a green building using the LEED assessment system in different regions, demonstrating the need to target different green building certification criteria for different regions to modify them to optimize local energy performance. Because assessing and processing multidisciplinary data before and during the project makes sustainability-assessment certification a time-consuming and complex process [151]. Moreover, high costs are incurred in the process of making changes in the different assessment phases [51]. Therefore, the data is structured and adapted to allow machine learning, and a certified building big data platform is created to populate the database of urban green buildings [9]. A summary of the research direction is listed in Figure 6.

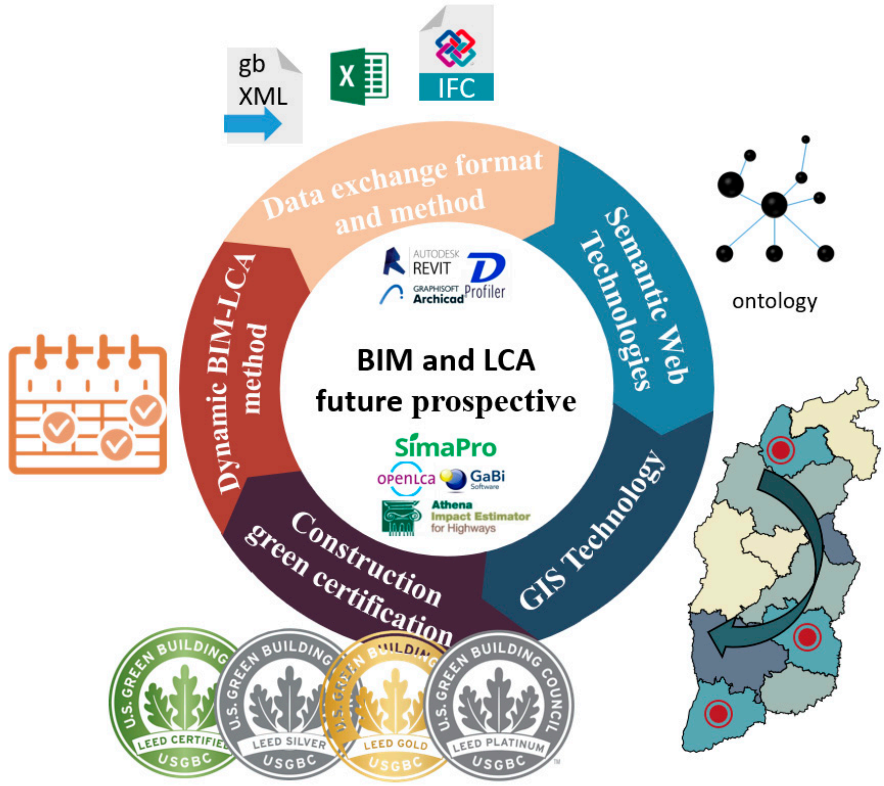

Figure 6. Future prospects of BIM-integrated LCA.

6. Conclusions

This review summarizes the features and limitations of three common BIM software and eight LCA tools, demonstrating that BIM software has excellent building information storage capabilities and data interactivity issues such as file output type limitations. LCA tools are good at quantifying the environmental impact of product objects. In contrast, each LCA tool has different LCI database support, evaluation calculation methods, compatible plug-in types, and output data methods. In addition, the types of energy consumption tools linking BIM–LCA are grouped together, and the data interoperability of the tools plays a crucial role.

This article concluded and analyzed five methods of BIM-integrated LCA, (1) BOQ import; (2) IFC import; (3) using BIM viewer; (4) using BIM plug-in to calculate LCA directly; (5) LCA plug-in calculation. Moreover, the collection outlines recent cases of applying BIM to integrate the LCA process and identifies the advantages of integrated applications to simplify the LCA process, check for model information errors, and improve construction sustainability. To further analyze the parameters affected by the integration between software, it was determined that models with lower LODs are suitable for the early design phase while determining the database criteria is beneficial to correspond to the appropriate LOD values. The semi-automated nature requires manual data mapping and avoids errors caused by default values during automation. Data exchange format and method is also another influencing factor; data exchange is important in three ways: (1) LCA information into BIM software with an API interface; (2) BIM software exports IFC format output to the LCA tool; and (3) to make BIM data and LCA data integrated into Excel or programming program format to export BOQ. It is important to determine the data exchange for existing tools for actual cases.

Finally, there are still issues with dynamic data processing, such as manual data collection, matching procedures, and overly simplistic LCA models. The current dynamic BIM software integration LCA tool evaluation needs to be integrated into the IoT big data information platform and broaden the database. Most of the ways to improve the interoperability of BIM and LCA software are still time-consuming and may have the potential for data loss and limited evaluation metrics. The standardized format of data exchange is an important direction for future integration. Automated semantic analysis applications are the way forward to address the challenges of manual data classification and reasoning in data exchange. The restricted application scenarios of BIM models and the level of automation and accuracy of semantic reasoning are the directions to advance BIM–LCA in combination with other technologies. Based on the integration of BIM software and LCA, integrating new technologies, such as semantic web technology and GIS technology, is conducive to enhancing technical performance and improving application efficiency. A unified green building certification system is difficult to determine, and structuring and adjusting the data is the key to optimizing the evaluation system.

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