Review

Digital Technologies and Sustainability Assessment: A Critical Review on the Integration Methods between BIM and LEED

Stefano Cascone

Department of Architecture and Territory, Mediterranea University of Reggio Calabria, Via dell'Università n. 25, 89124 Reggio Calabria, Italy; stefano.cascone@unirc.it

Abstract: In the context of sustainable development and parametric design, it is interesting to analyze the possible synergies between Leadership in Energy and Environmental Design (LEED), the most-used certification scheme for the design, construction, and management of green buildings, and Building Information Modeling (BIM), which supports the supply, integration, and management of information throughout the building life cycle. This paper aims to review the state of the art of the different integration methods between LEED and BIM at the early design phase. Third-party software information exchange, the cloud-BIM approach, and plug-in development using application program interface (API) were considered as possible integration strategies to automate LEED certification by BIM. In addition, optimization models and rule-based methods were analyzed. Finally, a critical review on the limitations, advantages and future research developments in LEED and BIM integration was clearly defined. Although the development of plug-ins was the most powerful integration method, it requires advanced informatics knowledge. On the other hand, using third-party tools increased manual working and checking due to interoperability issues. A visual programming language (VPL) can allow designers and researchers without any informatics knowledge to create parametric BIM models by including LEED requirements.

Keywords: building information modeling; parametric model; green buildings; leadership in energy and environmental design; information management; sustainable constructions; built environment; early design stage

1. Introduction

The construction industry is among the largest consumers of energy consumption and natural resources (i.e., energy, water, materials, and land) and buildings significantly contribute to CO_2 emission, leading to adverse impacts on the built environment [1,2]. Therefore, construction professionals have adopted new methods, technologies, and implementation options for designing green buildings to reduce environmental impacts, save the Earth's resources, reduce costs, and make contributions to occupants' health and comfort [3,4].

As part of the green transition of the built environment, many countries and international organizations developed various green building rating systems aimed at improving the sustainability and life-cycle performance of buildings and at mitigating the impacts on the environment [5–7]. However, the Leadership in Energy and Environmental Design (LEED) rating system, originally created in the United States, is the most recognized and commonly used protocol for the design, construction, and operation of green buildings [8]. LEED provides the certification criteria for eco-friendly and sustainable buildings and, therefore, its application is significant in the research community. As reported by the U.S. Green Building Council (USGBC), between January 2017 and December 2021, over 36,835 projects earned LEED certification, covering 4.63 billion gross square feet of space [9].

In addition to the green transition, the digital one meaningfully affects the construction sector and introduces complex challenges for the development of the built environment

and Building Information Modeling (BIM), one of the recent technological improvements in the management of construction projects, has become a significant tool to support the supply, integration, and management of information throughout the building life cycle [10–12]. The practical implementation of BIM by project teams in pursuing green building certifications, such as LEED, have attracted a lot of attention in the research community because the diverse project information included in the BIM model can be extracted to perform performance simulations, design reviews, quantity take-off and documentation generation, which are critical issues for obtaining LEED certification [13].

This paper's objective is to critically analyze the existing literature on the different integration methods between LEED and BIM. First, the main features of LEED and BIM are briefly described. As the early design phase is the most critical time to make decisions on building sustainability by evaluating the impact of different design alternatives, the research focuses on the possible integration strategies during this stage.

Third-party software information exchange, the cloud-BIM approach, and plug-in development using application program interface (API) are considered as possible integration methods at the early design stage. In addition, the optimization models and the rule-based methods to automate the LEED credit calculation with BIM are also considered. Finally, a critical state of the art, on the limitations and the future research developments on the existing LEED and BIM integration strategies, is clearly defined.

This paper is significant for both designers and researchers in improving the sustainability criteria from the early design stage of green buildings and in developing more advanced and ease-to-use methods to integrate LEED into BIM to speed up the documentation and certification process.

2. Previous State of the Art Studies

Recently, some researchers carried out systematic reviews on the possible integration of BIM with different green building certification systems, highlighting both the interest in this emerging research topic and the need to arrange the existing knowledge as a starting point for future research. After conducting an overview of both selected relevant publications between 2009 and 2020 and BIM software packages currently in use for evaluating sustainability, Ansah et al. [14] analyzed the criteria attainable with BIM in various rating systems and the degree of sustainable BIM implementation. The authors considered the database structure and information exchange. In addition, this was the first study combining the literature review with gap-spotting methods. This previous research revealed that designers need to exploit the use of BIM to automate building sustainability assessment, highlighting the absence of a unique method for BIM and green building rating-system integration. Interoperability issues were recognized as the main problems in encompassing the credits analysis in green building certifications. Carvalho et al. [15] created general knowledge concerning both which credit categories of several protocols were already practically evaluated within the BIM process and which software was usually applied to execute this process. To this aim, the appropriate articles between 2009 and 2019 examining the topic trends in terms of importance, used software package, selected journals, and adopted green building rating systems were identified. The authors concluded that, even with the expanded use of BIM to evaluate green building sustainability, there is still a skill gap among them because of the need to use several BIM tools. Finally, interoperability difficulties were also frequently observed, necessitating time for model testing during the early design phase. Olanrewaju et al. [16] analyzed the rate of publication of the chosen journals and categorized the papers based on the green building sustainability field and various assessment tools, primarily concentrating on earlier research related to transportation credits. In addition, a literature review on the extent of automated calculation of rating-system criteria and addressing the improvement of software suppliers was presented. As concerns the integration and criteria assessment, the most frequently used method was the application programming interface (API). Cloud-based approaches Microsoft macros and Dynamo (an in-built Autodesk Revit extension) were also appropriate for automating

the assessment procedure. Finally, Acampa et al. [17] focused on the potential integration between green building evaluation tools into BIM data systems. The integration procedure was reduced by the fact that only two of the existing ten categories set by LEED can be simply evaluated by BIM.

All these previous review studies mainly focused on the number of criteria and credits of different green building rating systems that it is possible to assess with BIM by identifying the most used commercial BIM software and the interoperability procedure between them. After analyzing the existing literature reviews, the following research questions were raised up and need to be addressed to fill the gap in knowledge:

1. What are the different integration methods that designers can adopt at the early phase to automate and speed up building sustainability assessment and certification?
2. What is the LEED-specific integration characteristic that should be specifically considered?
3. Among the integration methods analyzed, what is the most suitable that architectural designers can adopt to evaluate the impact of different alternatives on building sustainability at the early design stage?
4. What are the main limitations, advantages, and future research developments in integrating BIM and LEED?

3. Leadership in Energy and Environmental Design (LEED)

The U.S. Green Building Council (USGBC) created the first LEED green building rating system in 1998 to encourage sustainable construction [18]. LEED is a prescriptive system (versus performance-based approaches, such as LCA) for the design, construction, and operation of green buildings [19]. Not only does a design team have to design accordingly, but, in addition, they must document the procedure in a comprehensive way to meet certification review objectives. LEED has two important characteristics. First, it was established with an open consensus-based method, with feedback from a wide variety of building experts and other specialists. Second, and common to the other rating systems, employing LEED is voluntary and market-determined. One of the objectives behind creating the LEED system was to measure building performance and its impact on sustainability, performing facility management and a life-cycle perspective, which are important components of project-certification activities [20].

LEED employs an online platform based on points achieved in several categories. This system assesses the building performance and allocates points if the requirements are satisfied in nine credit categories of significant concern for sustainable development, including Integrative Process, Location and Transportation, Sustainable Site, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, Innovation and Regional Priority [21]. Each project must meet the prerequisites contained in every category and an optional number of credits. Almost 75% of credits in LEED are associated with the environment, while 20% are about social aspects. Just a few credits are linked with the economic pillar of sustainability [22].

LEED is constantly developing and from 2017 version 4 replaced version 2009. As new systems were created, LEED progressively turned into a set of rating systems focusing on the specifics of a range of building usages. The principles of each rating system in LEED continued growing and increasing as a consequence of the continuous improvement in technology sophistication, and the rationales behind and understanding of green building systems [23]. A distinct rating system exists for each one of the following: Building Design and Construction; Interior Design and Construction; Neighborhood Development; Building Operations and Maintenance; and Home. In addition, LEED deals with twenty-one building types, including: New Construction, Core and Shell, Schools, Retail, Data Centers, Warehouses and Distribution Centers, Hospitality, and Healthcare. Depending on the accumulation of points, successful projects are granted with the following levels of certification: Certified (40−49 points), Silver (50−59 points), Gold (60−79 points), or Platinum (80–110 points) [24].

4. Building Information Modeling (BIM)

In recent decades, parallel to the drive for green and sustainable construction, BIM offered a collaborative three-dimensional platform to help all stages of the construction process of green buildings be digitally modelled and investigated in a virtual environment [25]. With BIM, designers can make environmentally friendly choices at the early design stage of the building life cycle providing insight into how different design alternatives influence building sustainability and performance, thus avoiding the time spent for re-entering all the building information and the additional secondary data essential to performing the investigation [26]. Therefore, project members would be able to design, evaluate, organize actions, and identify potential conflicts among equipment and spaces within a three-dimensional digital environment. In addition, by employing BIM tools, owners can better follow the progress of their building design and construction phases [27].

Due to the richness of the multidisciplinary information, developing a three-dimensional parametric model within BIM enables information-centric project management in contrast to the conventional document-centric method because it acts as a central storage of project-related information to produce documentation which project members need to examine to consequently adapt the building design before its physical implementation [28]. In addition, designers and engineers can efficiently integrate, manage, and share information between architectural, structural, electrical, mechanical, construction, design, and facility-management teams through the building life cycle within an integrated working system and, in this way, the sustainability analysis can be reliably integrated into the design process [29].

Sustainable strategies combined with BIM can create a high-performance and efficient building design while replacing the conventional drawing-based design. To accomplish this objective, parametric modelling has been recognized as a useful tool as it produces adjustable models which can be combined with assessment, optimization, and automation tools [30]. Sustainability demand is also referenced by software vendors. Several parametric modelling tools based on 3D software are commercially offered for the management of either the whole project or only a specific part of its life cycle. Between them, Revit is largely utilized by owners, suppliers, engineers, and designers, among others, to generate parametric models.

BIM data can be integrated with building performance and simulation applications, such as Autodesk Green Building Studio, Ecotect, Autodesk Project Vasari, IES-VE, and Bentley AECOSim, etc. This integration allows them to be effective decision-making tools for the design of high-performance buildings. Additionally, these tools may be widely personalized through plug-ins, which expands their initial capabilities. These plug-ins, usually designed by third parties, allow the inclusion of performance simulations within the BIM environment, facilitate problem solving using optimization methods, and can significantly automate processes [31].

Numerous information levels and data are entered into BIM models, which are called BIM dimensions [32]. These dimensions are the following: 3D: the third dimension, including geometric, graphical, and nongraphical information; 4D: the fourth dimension, including timeline, scheduling, and extent; 5D: the fifth dimension, comprising cost assessment; 6D: the sixth dimension, including sustainability; and 7D: the seventh dimension, including facility management during the project life cycle. Apart from these dimensions, BIM also implies five levels of development (LOD), which is an industry standard specifying how the 3D geometry of the building model can accomplish numerous levels of sophistication [33]. These LODs are as follows: LOD 100, including building location and space; LOD 200, including quantity, size, and form, among others; LOD 300, used for clash finding, scheduling, and visualization, among others; LOD 400, including MEP systems; and LOD 500, including building operation and maintenance.

5. Integration Methods for Automated Assessment

This literature review was based on the Scopus database. "BIM" and "LEED" were used as search terms within article titles, abstracts, and keywords. Other terms were used for the search (such as Building Information Modeling, Building Information Modelling, and Leadership in Energy and Environmental Design, etc.) but the results using the terms "BIM" and "LEED" always returned the other papers due to the wide use of these acronyms.

The timespan of the research was 2012–2023 and only the article and review papers published in scientific journals were considered, therefore excluding conference papers and book chapters, etc. In this way, 54 papers were selected and analyzed. After the analysis, 19 papers were selected as relevant for this literature review and described in the following paragraphs (Table 1). Among these, 11 papers analyzed the integration between BIM and LEED using third-party applications. As concerns the most-adopted software, Autodesk Revit Architecture was broadly chosen as a BIM tool by all the integration methods.

Table 1. Summary of the 20 relevant publications.

Ref.	Title	Integration Method	Software	Case Study
[34]	Building information modeling for sustainable design and LEED rating analysis	Third-party software	Revit Architecture, IES-VE	Perdue School of Business, Salisbury University
[35]	Leveraging cloud-BIM for LEED Automation	Cloud computing	-	-
[36]	Integrating building information modelling with sustainability to design building projects at the conceptual stage	Third-party software	Revit Architecture, Microsoft Excel, Athena Impact Estimator	Six-floor apartment-building project, Ottawa
[37]	BIM execution planning in green building projects: LEED as a use case	Cloud computing	-	-
[38]	Integrating building information modeling (BIM) and energy analysis tools with green building certification system to conceptually design sustainable buildings	Third-party software	Revit Architecture, Autodesk Ecotect, IES-VE, Microsoft Excel, Athena Impact Estimator	Eight-floor residential apartment-building project, Ottawa, Canada
[39]	Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings	In-program plug in	Revit Architecture	Four-floor residential-complex project, Toronto, Canada
[40]	Rapid LEED evaluation performed with BIM based sustainability analysis on a virtual construction project	Third-party software	Revit Architecture, Revit MEP, IES-VE, Project Vasari	Museum of Architecture, Doha
[41]	Framework for sustainable low-income housing projects using Building Information Modeling	Rule based	Revit Architecture	Low-income housing project, Badr City, Egypt
[42]	Green building and biodiversity: facilitating bird friendly design with building information models	Third-party software	Revit Architecture, Dynamo	-

Table 1. *Cont.*

Ref.	Title	Integration Method	Software	Case Study
[43]	Pedagogy and assessment of student learning in BIM and sustainable design and construction	Third-party software	Google Earth, Revit Architecture, Green Building Studio,	Campus project
[44]	Integrating web map service and building information modeling for location and transportation analysis in green building certification process	In-program plug-in	Google Earth, Revit Architecture	Wafer-factory project, Taiwan
[45]	BIM-based approach for optimizing life cycle costs of sustainable buildings	Rule based	Revit Architecture	University building, Saudi Arabia
[46]	Building information modelling for an automated building sustainability assessment	Third-party software	Revit Architecture, Dynamo	University building, Porto, Portugal
[47]	MSOT: materials selection optimization in the LEED v4 protocol—a case study with BIM	Third-party software	Microsoft Excel	Meeting center, Italy
[48]	An integrated BIM-LEED application to automate sustainable design assessment framework at the conceptual stage of building projects	In-program plug-in	Google Earth, Revit Architecture, Green Building Studio	Office building, Calgary, Canada
[49]	Incorporating BIM and green building in engineering education: assessment of a school building for LEED certification	Third-party software	Revit Architecture	University building, Turkey
[50]	Rule-based LEED evaluation method considering BIM linkage and variability	Rule-based	Revit Architecture	-
[51]	On the exploration of Building Information Modeling capabilities for promoting sustainability-related practices in construction projects: case studies in China and USA	Third-party software	Google Sketch-Up, Revit Architecture	128-story tower, Shanghai, China 13-story building, San Francisco, USA
[52]	A multi-facet BIM based approach for Green Building design of new multi-family residential building using LEED system	Third-party software	Revit Architecture, Green Building Studio, Insight	Luxurious home buildings, Pakistan

The extent of selected papers is consistent with the previous review studies, demonstrating that conducting a review on the integration between BIM and LEED is work of interest for the scientific community. The flowchart illustrating the research methodology and all used analysis is shown in Figure 1.
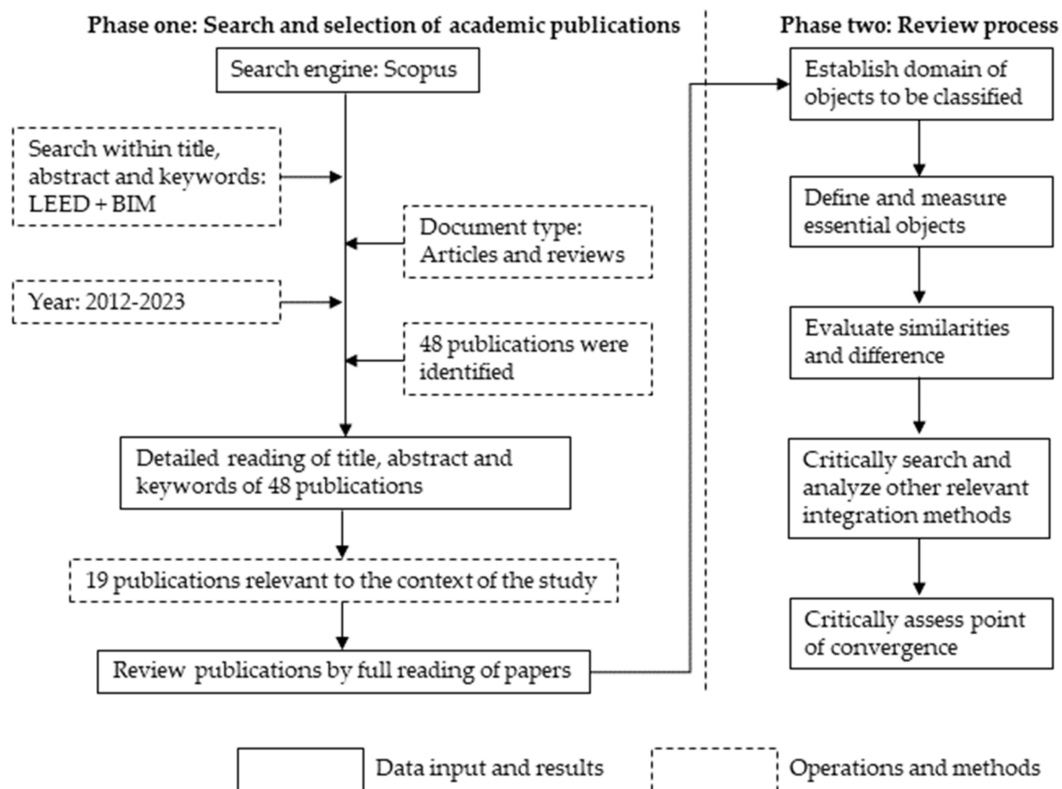
Figure 1. Methodology flowchart.

5.1. Third-Party Software

5.1.1. Commercial Software as a "Black Box"

Utilizing third-party software is the most common method to assess LEED credits. A project team can take advantage of the software platform to perform required LEED estimates for credits that need comprehensive numerical evaluation, such as energy simulation, lighting evaluation, water utilization, material characteristics and integrated design. The practice of coordinating BIM software and LEED credit requirements is an initial step in the integration between BIM and LEED.

However, this integration method rarely moves ahead from the specific project due to the temporary structure of the design team, which makes the accomplishment hard to reproduce. The existing workflow consists of developing and designing a building information model using specialized BIM software (i.e., Autodesk Revit) and then repackaging it as an analytical model which can be transferred to specific software, to perform analysis using third-party software. The outputs from this software can be used in green building design and certification, such as LEED, to determine the points achieved. A conventional file interface was created by Autodesk to help the file transfer procedure (i.e., gbXML) which is commonly recognized and utilized by AEC professionals. Among the various commercial software, the authors noticed that Integrated Environmental Solutions (IES-VE) and Autodesk Green Building Studio were the most suitable software for LEED integration.

BIM is mostly capable of building performance assessments and not relevant to other LEED categories and manual processing is still needed for changing between software and information importation and exportation. The major obstacle to BIM and LEED integration is the variety of software and domain data required for field-specific building simulations and assessments. Even though collaboration among software vendors and the use of proprietary file formats in some way alleviate the problem, chances are the difficulty of LEED projects may ultimately create confusion and miscommunication among project members, should there be no careful preparation of model-data exchange mechanisms. The key is to produce an interoperable software environment founded on open standards

such as Industry Foundation Classes (IFC) to ease unified and bidirectional data flow among separate project members, meeting individual model-data requirements in real time without compromising the global design process, the model integrity or the expected building performance as set in the LEED protocol.

Azhar et al. [34] developed a theoretical framework for determining the relationship between BIM-based sustainability evaluation and LEED credits and confirmed this framework through a case study. The framework involved the use of Autodesk Revit Architecture for building modeling and Integrated Environmental Solutions Virtual Environment (IES-VE) for energy and atmosphere, water consumption and daylighting credit assessments which can be detailed utilizing outcomes from BIM software. Up to 17 LEED credits and 2 LEED prerequisites may be directly, semi-directly and indirectly gained using findings produced by BIM software. However, due to the restricted availability of building information, the authors confirmed only five credits and one prerequisite, achieving a total of 17 points.

It is in-line with this previous study, even if in a different geographic area, that Alwan et al. [40] described an effort to simplify the environmental evaluation process by studying useful techniques using the presence of existing BIM information, which was transferred among software tools employing the gbXML format. This earlier research included 14 LEED credits using various BIM software.

An approach to the creation of an integrated model that streamlines the procedure of creating green buildings at the conceptual phase, including BIM, LCA, LEED, and cost modules, was implemented by Jrade and Jalaei [36]. Every component was associated to an external database collecting LEED information on green materials and certified elements. This information was employed for designing families and keynotes in Autodesk Revit Architecture with functional, technical, and economic description of sustainable materials applied in the BIM model.

Later, the same research group [38] revised the model with an energy and lighting module. In addition, part of the procedure was to create new plug ins to transfer a BIM model based on the gbXML and IFC formats directly into the analysis software. The authors used Ecoscorecard in Autodesk Revit to assess the elements and the model permitted recognition of the achieved points in the LEED rating system. In these studies, several types of software were used, such as Revit Architecture, Ecotect, Integrated Environmental Solutions (IES-VE), Microsoft Excel and Athena Impact Estimator, for the creation of the integrated model. This model allowed users to evaluate and choose various materials and elements, which were collected in the database, to be applied in their project based on sustainability requirements and costs.

Raimondi and Aguerre [47] suggested a device, MSOT (Materials Selection Optimization Tool), a comparative Microsoft Excel matrix, and a method to help the designer in materials choice aiming to reach the highest LEED score and material sustainability through the Revit model information extraction. The quantities were obtained directly from the BIM file and an abacus (Excel file) with the list of materials was acquired. This list was arranged in MSOT according to the incidence on the cost and on the LEED credits accomplishment.

Alfalah et al. [51] examined case studies in order to examine the effectiveness of the developed BIM-based model. The design team applied Google Sketch-Up in their daylighting modeling, and then they transferred them from Google Sketch-Up into Revit. The designers attained LEED Platinum certification.

Finally, Ur Rehman et al. [52] identified and implemented methods to accomplish green building parameters for energy and water saving for multi-family houses provided by the LEED certification scheme with the assistance of BIM tools, i.e., Autodesk Revit, Insight and Green Building Studio.

5.1.2. Student Education

Several studies assessed student knowledge on BIM with the single intention of examining interactions among BIM and sustainable design and construction. Wu and

Luo [43] evaluated student knowledge on BIM with the unique intention of examining interactions among BIM and sustainable design and construction. The whole methodology was to use an on-campus project to simulate the LEED project delivery and BIM project process in which design teams carry out basic assignments in pursuit of LEED certification with BIM as a facilitator. The technology chosen for the project was Autodesk Revit for model authoring and materials take-off and Autodesk Green Building Studio for energy simulation, water efficiency calculation and daylighting simulation.

Differently, Atabay et al. [49] evaluated and reevaluated for design and construction stages the Yildiz Technical University Faculty of Civil Engineering building according to LEED certification, using the Revit BIM-based tool. For this reason, the authors examined the agreement with LEED v4 BD+C: Schools certification system through 3D modeling and acknowledged that the construction phase also contributed greatly to the LEED certification procedure.

5.1.3. Visual Programming Language (VPL)

Since a visual programming language (VPL) allows featuring a third party without any skills in C-coding language (as shown later with plug ins), several researchers adopted it to streamline the integration process. Kensek et al. [42] demonstrated an application of BIM for LEED by means of a VPL as an intermediary. Autodesk Dynamo is an example of a VPL intended for use with Autodesk Revit. The authors conceived a Dynamo "graph" to assess if a building developed in Revit would gain points for the LEED Pilot Credit 55: Avoiding Bird Collisions. The LEED Pilot Credit aims to enable the establishment of new credits in LEED. The procedure permits projects to assess more advanced credits that have not been through USGBC's completed drafting and balloting process. The Dynamo tool obtained the required data from the Revit model and determines a "Pass" or "Fail" for LEED Pilot Credit 55. A BIM tool to automate LEED credits, concentrating on the credits associated to stormwater runoff, was established by Sanhudo and Martins [46]. For this purpose, Revit as BIM model inventor, Dynamo as visual programming language behind the software, and Dyno as user interface were used.

5.2. Cloud-Computing

Recent advancement in BIM server technology and the popularity of cloud computing have catalyzed the shift in desktop BIM applications to be implemented over the cloud. Cloud computing is a model for allowing accessible and on-demand web access to a shared collection of configurable computing resources that can be quickly provisioned and released with negligible management effort or facility–provider collaboration [53].

Meanwhile, in apprehension of the lacks in the current LEED certification workflow, USGBC modernized their LEED project-management device, LEED Online, and proposed a new commercial product of LEED certification called LEED Automation, to accommodate the amplified use of BIM tools and rationalize the certification process. These adjustments were identified as occasions by BIM and LEED specialists to strengthen the existing achievement of integrating BIM and LEED, and to move forward to the next stage assisted by a more effective and adaptable cloud organization [54].

Architectural projects, especially BIM-based projects, could benefit from the availability of online common services, such as sharing the BIM model across the design teams contributing to any BIM projects, or other server-based applications that permit the employer to automate a portion of their workflow, either in design or in documentation preparation for LEED certification [55]. Existing advancement of BIM cloud technology follows this trend, cloud-based BIM applications and BIM servers are being created to meet the demands of architectural designers.

Wu and Issa [35] proposed a framework aimed at leveraging the cloud-BIM technology for LEED Automation using leading-edge technology and best practices. With completing LEED certification as the default project target, the authors examined and chose the cloud approaches. The framework was constructed upon BIM server technologies, architectural

cloud structures, committed architectural SaaS solutions that are offered in the market, and standard data-exchange processes/procedures. The proven completion of the recommended framework delivers a most thorough development of the LEED project supply method. In another study, Wu and Issa [37] established a unique BIM process model to encourage green BIM procedures and enhance LEED project results. The authors aimed to revise the BIM project-execution planning guide's principles and standards for green building projects, particularly LEED projects, to support and assist green BIM procedures. An integrated green BIM process map and validation of its potential execution with LEED as a use-case through exemplary case studies was suggested. Step 1 of the process recognizes the LEED certification and credits business objectives and possible BIM usages while Step 3 presents the process-specific BIM uses determined by certain LEED credit requirements, designates responsible parties, and spells out the data-exchange approach and the predictable process results. Cloud-BIM has become a new trend in the architecture business and has provoked significant consideration of BIM experts on BIM application and growth. It is assumed that as the LEED certification market maintains its growth, better and more profitable policies to achieve LEED certification can be prepared based on the smarter technology and process presented by cloud-BIM.

5.3. In-Program Plug In

One of the most useful statements about BIM software is that plug ins can be simply used by a qualified computer programmer for different requests. In pursuit of LEED certification, some plug ins for different software were created to improve the efficiency of architectural designers and reduce the time spent on preparing LEED-certification-associated procedures.

The term "plug in" applied in the BIM tool implies a module including a process that makes use of the BIM tool's application program interface (API), which offers data exchange to various programs. Autodesk Revit API has enabled the industry to manage various type of integrations and evaluations of several areas by permitting the user to write software in any. API can assist developers in expanding the functionalities of BIM authoring software. API lets users obtain information directly and repeatedly from BIM models for various objectives. Using API, users can answer the abovementioned difficulties for the integration of BIM and LEED: the restricted functionalities of existing BIM software and the necessity of manual changing among products and data importation/exportation. Currently, a BIM model includes a project's location coordinates and other data that are required for energy consumption, lighting, views, orientation, and thermal assessments. For example, in Revit, site coordinates and overall building areas are accessible through the "Project Location" and "Area" dialog boxes. This data can be obtained through BIM API functions and linked with map functions for Location and Transportation evaluation in the LEED certification procedure.

Jalaei and Jrade [39] established the first model dealing with LEED at the early design phase by applying the API of BIM software. This model automates the procedure of finding the required number of points based on the designated LEED certification categories, collects all the chosen credits/points along with proposing the qualified certification type in the format of a plug-in within the BIM platform, Revit Architecture. All the data accessible in the model, such as the design data and LEED information of the construction elements, are collected in an exterior database related to the BIM software. The established plug in improves the LEED choices, immediately determining whether the existing design can theoretically receive the LEED points. In the accomplishment of this earlier effort to improve BIM and LEED integration in the direction of being completely automated by applying the API of the Revit software and the C# coding by means of the Visual Studio environment, Jalaei et al. [48] suggested a method to evaluate a possible LEED certification system while giving a framework for determining the points in agreement with BIM at the early design stage. After information collection and the input of data for the BIM model together with an expanded database for several materials, an advanced plug in was created to determine the

possible collected LEED points with access to the API of Autodesk Revit and Google Map. The credits were calculated by the proposed plug-in by assembling responses from the BIM model; Google Maps data for the project site evaluation; the embedded list requests in the plug in; and the energy, glazing factor, and water-efficiency assessment findings from Autodesk Green Building Studio. This research, moreover, proposed a procedure to estimate the possible LEED points for the criteria that are not usually quantifiable from the design data by means of the distance-weighted k-nearest neighbor (DWKNN) technique in the backend of the proposed plug-in device by assessing 76 LEED-certified projects. The authors determined that 94 points make use of KNN and BIM-based solutions. The plug-in additionally indicated the rescaled amount out of 110 by employing a linear rescaling factor in addition to recommending the highest number of points the project can theoretically receive. It was the first model that deals with all of the LEED v.4 categories and related certification levels, saves users' time, and decreases users' work.

The integration of BIM and LEED with the help of Web Map Services (WMS) was studied by Chen and Nguyen [44]. The established BIM–LEED framework and plug in could assist the determination of the points of the two most significant credits in the Sustainable Sites category for site and transportation assessments in a useful manner. The authors implemented Autodesk Revit (BIM) and Google Maps (WMS) due to their attractiveness. The plug-ins were internally integrated into the customer interface of Autodesk Revit, and BIM information was quickly extracted to assist in mechanically computing LEED points. With these plug-ins, no manual changing among BIM software nor manual computation of LEED points were necessary.

Although the plug ins may be the most useful tool for BIM customers as an evaluation tool, there is yet an exceptionally long path to go before they can contend with third-party software and the other techniques.

6. Optimization Models and Rule-Based Methods

The investigation of the current research paper showed that BIM information is obtained by means of tools such as Autodesk Revit plug-in, and the building performance assessment logics are employed via hard coding [56]. In addition, commercial software is hidden in black boxes for LEED assessment. For instance, several software, such as Ecotect, are specifically just for computational simulations such as daylight analysis [57].

For LEED building performance assessment, the required BIM information sources and calculation methods may differ in relation to the usage situation. If the BIM information sources or assessment methods can be described in terms of a general operator, the assessment processes will be identified based on procedures; thus, solutions will not vary and BIM-linked building performance assessment can be automated. In addition, the hard coding term is utilized to differentiate this from the commercial system, where the customer cannot modify the assessment rule.

Marzouk et al. [41] suggested a framework comprising four major parts: BIM; Project Duration Simulation; LEED optimization; and System Dynamics. The BIM model was created by means of Autodesk Revit and the various material information was obtained from the developed model, permitting LEED credit estimation. The LEED materials calculator applies the predefined sustainable material information to determine the LEED points attained. To choose the ideal building materials that obtain the highest LEED credit, an optimization model was built using a Microsoft Excel plug-in which employs an NSGA II genetic algorithm to resolve several objective questions. NSGA II is a multi-objective optimization algorithm centered on non-dominated sorting. The findings showed that the operational costs of sustainable materials were much less than those from the conventional materials. In a similar way, the same research group [45] implemented the integration of economic and environmental criteria utilizing BIM, optimization modeling, and Monte-Carlo simulation. The BIM model was created employing Autodesk Revit and the various material information such as quantities and LEED documents were obtained from the model. The optimization model was created using a genetic algorithm to choose the ideal

building options that had lowest LCC and highest LEED credit points. The optimal scenario had an overall cost of 9 credit points out of 11 points accessible in LEED.

The concept of a rule-based LEED evaluation method with BIM (RLEM-BIM), which identifies and automates the LEED certification procedure based on general rules, was suggested by Kang [50]. This approach permitted identifying and automating assessment rules which can help the flexibility of LEED projects. The authors reported that RLEM-BIM increased in terms of its adaptability and reusability, and it aided a reduction in mistakes and the manual-labor rework amount.

7. Critical Analysis on BIM-LEED Integration

7.1. Limitations

First, no one-to-one connection exists between LEED certification and BIM-based sustainability evaluations (except for daylight analysis with Revit) due to the absence of LEED integration characteristics in the existing BIM software. Missing data put through the conversion procedure from BIM software to others comprises data necessary as input by several third-party tools and, therefore, some data needs to be filled in physically by the designer following the transfer procedure while other data are directly adopted by the software (such as data regarding the materials shifting from Revit to Ecotect or IES-VE). In addition, some differences between software and manual environmental evaluations are documented, mostly due to the imprecision of building information models. Therefore, designers are advised to always carry out manual tests to prevent any errors in the LEED certification process.

As concerns the framework leveraging the cloud-BIM technology for LEED Automation, it is limited as no validation was feasible due to the absence of relevant case studies. In addition, the previous research on business processes focused on BIM execution in LEED projects was also restricted in numerous aspects. The first and major constraint is the absence of manufacturing involvement in the development of the proposed integrated green BIM process map (IGBPM). Second, most level-2 process maps have not been fully established so far. Third, the suggested IGBPM did not deal with the application of open standards such as IFC, which could have been a main contribution to the body of expertise. Lastly, the proposed IGBPM requires supplementary validation with quantifiable project data and a system of measurement that clearly demonstrates the effects of the combined green BIM execution on LEED project results.

The main constraint of the model integrating BIM and LEED applying in-program plug ins is that it can be used only at the early design phase of a project since its database does not cover all LEED materials. Furthermore, the established database was created based on few stored BIM objects including a reduced number of certified elements, all of which are conceived and supplied by the companies. This implies that there are numerous sustainable BIM families that need to be created and imported into BIM files and implemented into the database. A further drawback is in the automation of energy- and water-efficiency outcomes among Green Building Studio and Revit since the CSV exported file format of Green Building Studio does not contain the glazing factor, monthly energy consumption and water efficiency, which gain LEED points. Therefore, the transmission of data from Green Building Studio to the plug-in should be manually performed by users. To achieve well-balanced building performance, BIM improvement requires reinforced endeavors for the complete range of concerns in building design and construction.

Finally, the optimization analyses had the shortcoming of not assessing several LEED projects and evaluation situations. In the future, the suggested approach should be applied to the analysis of the building-environment assessment platforms for verifying the use impacts based on different circumstances. In addition, LEED assessment based on RLEM-BIM must have the appropriate information in advance and be free from information-reliability difficulties. For this purpose, the requirements for executing RLEM-BIM are crucial.

7.2. Advantages

The major advantages are the following:

1. BIM-based sustainability software produces findings rapidly when compared to the conventional techniques. This could save considerable time and resources.
2. The technology core of the cloud-BIM leveraged LEED Automation framework can be deemed well-established and broadly accepted in the industry.
3. The model integrating BIM and LEED was easy and accessible as user inputs and mistake prediction are reduced. Time decrease, quick computations, and expert output reports are some of its benefits.
4. There are numerous significant advantages to creating simultaneous environmental calculations throughout the early phases of the design process, mostly being able to attain an initial understanding in a design process and have the solutions maintained during the construction phase or by permitting choices to be changed.
5. Integrating BIM with optimization modeling and Monte-Carlo simulation facilitates the decision maker in choosing the optimal building materials that accomplish the environmental and economic sustainability of the building when evaluating various design options.
6. Even though visual programming languages, such as Dynamo, offer a simple available platform for parametric modelling, conventional coding languages and plug ins present additional functionality and adaptable code, especially in complicated uses. Despite this, Dynamo still shows itself to be a useful tool for the automation of simpler project-associated tasks, because of its simple entry as Revit model data and no required earlier software-development expertise.

7.3. Future Research Develpment

Upcoming research should be concentrated on the verification of LEED credits and prerequisites which may be gained through BIM-based sustainability assessments and on the application of different software (such as Ecotec, Green Building Studio, etc.) to define which one is highly effective for a certain kind of evaluation. In addition, more effort is advised to maintain such analyses and expand the ability to exchange information among BIM software and LEED.

As concerns the cloud-based technology, it will be helpful to conduct a business process modelling study to take a closer look at the inferences of the cloud-BIM-eased LEED project delivery for diverse project stakeholders, particularly the data flow and exchange needs throughout this procedure. Interoperability problems have not been adequately examined. Additionally, prior to the framework leveraging the cloud-BIM technology for LEED Automation being applied more broadly, its confirmation and evaluation versus real-case situations should be performed.

The research in the plug-in area is in progress, and authors are presently involved in developing the databases related to the established model in addition to attaining a complete automated integration among the various tools necessary to take part in sustainable conceptual design for building projects.

Additional possibilities for the customization of the software are also in progress: use of various economic assumptions; establishment of a user interface for revising the database immediately; and developing the database to supply additional countries' parameters and modernizing the interface, amongst others. The design of a unified database to help the software is also intended.

Future research will involve integrating building information modeling and various artificial-intelligence tools as machine-learning models and deep-learning models to imitate the prominent aspects of LEED-certified buildings. Additionally, metaheuristics can be hybridized with building information modeling for the sake of the optimal choice of materials in an effort to improve the LEED rating of buildings.

8. Conclusions

This paper analyzed the existing literature to identify the possible integration between LEED and BIM. Third-party-software data exchange, the cloud-BIM method, and plug-in development using application program interface (API) were considered as potential integration techniques at the early design phase.

The outcomes demonstrated that there are no suitable tools integrated into BIM software (i.e., Revit Architecture) to fully automate LEED certification. The plug ins currently included allow for determination of only a few LEED credits (e.g., Insight 360 for some energy-related LEED credits and the Daylight tool after paying the fees). Although the development of new plug ins by means of API is the most powerful integration method between BIM and LEED because the users can adapt authoring software to every project need, designers and researchers found it difficult to use since it requires advanced informatic knowledge (C# coding language) and these new plug ins are not commercially available for researchers and designers as they are owned by the developers.

On the other hand, using third-party tools through the information exchange between different BIM software can increase the manual working and the checking time due to model information transfer and interoperability issues. In addition, it is necessary to integrate several tools for LEED credit evaluation (i.e., Green Building Studio for energy and water simulation, and Revit Architecture for material computation and daylight analysis, etc.).

The use of a visual programming language (VPL), such as Dynamo for Revit Architecture, can solve the problem related to the interoperability issues since the model is developed into a unique virtual environment and, at the same time, can allow designers and researchers without advanced informatics knowledge to create a parametric BIM model by including LEED credits and categories.

Finally, the research proved that the knowledge of the cloud-BIM for LEED automation can be deemed well-established and broadly implemented in the AEC industry and several authoring software, such as Autodesk, are adopting this new business paradigm.

Future studies should be focused on the possible integration methods between BIM and other green building certification schemes, such as BREEAM, ITACA, etc.

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