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BIM-BASED ENERGY ANALYSIS AND DESIGN TOOLS FOR LEED CERTIFICATION

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Abstract: Green building rating systems (GBRSs) are developed to assist Architecture, Engineering, and Construction (AEC) professionals to measure building performance and fulfill the requirements of sustainable design and construction. Designing high-performance buildings according to GBRSs with the use of Building Information Modeling (BIM)-based energy analysis and design tools promotes sustainable construction, helps reduction of carbon footprint, and overall eases the green building certification process. Although previous studies addressed the use of BIM in LEED (Leadership in Environmental and Energy Design) certification; limited number of studies focused on using BIM-based tools for examining credits and requirements of LEED v4. The objective of this study is to demonstrate in what ways BIM-based energy analysis and design tools can support project teams in pursuit of LEED certification for residential projects. A literature review and case study were conducted, and Autodesk Revit Green Building Studio, eQUEST, EnergyPlus, and IES-VE tools were examined in terms of achieving LEED v4 Building Design and Construction for Multifamily Midrise rating system credits. Results demonstrate that these tools can perform 17 LEED credits. This study determines the pros and cons of these four BIM-based tools in terms of the LEED v4 BD+C MM rating system. This study also contributes to the AEC industry and literature with four decision-making flowcharts that are developed as guidelines for AEC professionals to conduct BIM-based LEED certification processes more effectively.

Keywords: BIM, Building Information Modeling, LEED, Green Building Rating Systems, Energy analysis, Residential buildings

LEED Sertifikasyonu için BIM tabanlı Enerji Analizi ve Tasarım Araçları

Öz: Yeşil bina derecelendirme sistemleri (YBDS), mimarlık, mühendislik ve inşaat profesyonellerinin bina performansını ölçmelerine ve sürdürülebilir tasarım ve inşaat gereksinimlerini karşılamalarına yardımcı olmak için geliştirilmiştir. Yapı Bilgi Modellemesi (YBM) tabanlı enerji analizi ve tasarım araçlarının kullanımıyla YBDS'ye göre yüksek performanslı binalar tasarlamak sürdürülebilir inşaatı teşvik eder, karbon ayak izinin azaltılmasına yardımcı olur ve genel olarak yeşil bina sertifikasyon sürecini kolaylaştırır. Önceki çalışmalar, LEED sertifikası için YBM kullanımını ele almış olsa da; sınırlı sayıda çalışma LEED v4'ün kredilerini ve gereksinimlerini incelemek için YBM tabanlı araçları kullanmaya odaklanmıştır. Bu çalışmanın amacı, YBM tabanlı enerji analizi ve tasarım araçlarının konut projeleri için LEED sertifikası alma yolunda proje ekiplerini hangi yollarla destekleyebileceğini göstermektir. Bunun için literatür incelemesi ve vaka çalışması gerçekleştirilmiş; Autodesk Revit Green Building Studio, eQUEST, EnergyPlus, ve IES-VE araçları LEED v4 Bina Tasarımı ve İnşaatı (BD + C) Multifamily Midrise (MM) derecelendirme sistemi kredileri açısından incelenmiştir. Sonuçlar, bu araçların 17 krediyi gerçekleştirebileceğini göstermektedir. Bu çalışma, LEED v4 BD + C MM derecelendirme sistemi kredileri açısından bu dört YBM tabanlı aracın artılarını ve eksilerini belirlemektedir. Bu çalışma ayrıca inşaat sektörü uzmanlarının YBM tabanlı LEED sertifikasyon süreçlerini daha etkin bir şekilde yürütmeleri için

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yol haritası olarak geliştirilen dört karar verme akış şeması ile inşaat sektörüne ve literatüre katkıda bulunmaktadır.

Anahtar Kelimeler: YBM, Yapı Bilgi Modellemesi, LEED, Yeşil bina derecelendirme sistemleri, Enerji analizi, Konut binaları

1. INTRODUCTION

Buildings and construction industry is responsible for almost 40% of energy- and process-related emissions. 2019 Global Status Report demonstrates that the sector is not on track with the necessary level of climate action (International Energy Agency, 2019). According to the Organization for Economic Co-operation and Development (OECD), "natural resource consumption in the construction industry has increased 80% since 1980 compared to a 60% increase in overall resource consumption" (Redmond, 2016). Hence, the construction industry has begun to put more emphasis on sustainability with the aim to reduce raw material consumption and greenhouse gas (GHG) emissions.

The principles of sustainable construction consist of reducing resource consumption, reusing resources, using recyclable resources, protecting nature, eliminating toxics, apply life-cycle costing, and focusing on quality (Kibert, 1994). Hence, green building rating systems (GBRSs) are developed to assist professionals to measure building performance, and fulfill the requirements of sustainable design and construction. Different GBRSs have similar purposes such as verifying environmental performance of buildings, using natural resources efficiently, estimating and forecasting the energy performance of buildings and encouraging more energy-efficient building designs.

GBRSs-based high-performance building projects require detailed modeling, additional specification requirements, and tracking numerous aspects of the construction process, such as construction waste management, indoor air quality protection during construction, erosion and sedimentation control, quantities of recycled materials and emissions from materials (Kibert, 2016). Building Information Modeling (BIM) provides a platform for these by, for example, ensuring designers select the optimum building orientation in order to maximize renewable energy generation and daylighting, and accordingly minimize energy consumption. Additionally, BIM can increase the uptake of green buildings by lowering costs (Kibert, 2016). Designing high-performance buildings according to GBRSs with the use of BIM-based energy analysis tools promotes sustainable construction, help reduction of carbon footprint, make the green building certification process much easier, and support the economy (Kibert, 2016; Wong *et al.*, 2013).

Some of the previous studies have discussed the differences between the two well-known GBRSs, namely BREEAM (Building research establishment environmental assessment method) and LEED (Leadership in environmental and energy design), in terms of their scoring systems and assessment of credits in the certification process (Raslan *et al*,, 2013; Jalaei *et al.*, 2020). Some of them have compared the different versions of ASHRAE standards within the scope of LEED (Rastogi *et al.*, 2017). A few of the studies developed tools to evaluate indoor environmental quality performance (Larsen *et al.*, 2020) while some of them reviewed the literature for providing the effects of BIM in building performance analysis (Jin *et al.*, 2019) in terms of different aspects, such as water, space heating, lighting, carbon emissions, acoustics, and location (Raslan *et al.*, 2013; Azhar *et al.*, 2010; Rezaallah *et al.*, 2012). However, a limited number of studies were conducted to examine in detail the credit information and requirements of LEED v4 by using BIM-based energy analysis and design tools, even though LEED requires several calculations to be performed in order to achieve a certain level of certification (Rezaallah, 2012).

The objective of this study is to demonstrate in what ways BIM-based energy analysis and design tools can support project teams in pursuit of LEED certification for residential projects. For this purpose, a literature review was conducted and a case study building was used to evaluate the selected BIM-based tools in the LEED process. Within the scope of this study, the most commonly used and well-known BIM-based tools are analyzed for the LEED v4 certification system. Cost analysis for the credits, and “Location and Transportation”, “Integrative Process” and “Innovation” categories are out of scope of this study. “Location and Transportation” requires performing detailed data collection and comprehensive studies on the logistics of the building that cannot be applied in this study. Credits in the “Integrative Process” and “Innovation” categories are not able to be implemented within the scope of this study due to their unique features. This study contributes to the Architecture, Engineering, and Construction (AEC) literature and industry practice by providing four decision-making flowcharts that support construction professionals in pursuit of the LEED certification process and designing more energy-efficient residential buildings. Results of this study will likely encourage the use of BIM-based energy analysis in the AEC industry. The target group of this study involves contractors, engineers, site managers, designers, architects, energy assessors, LEED consultants, and all other professionals who intend to achieve LEED certification for their new buildings.

2. LITERATURE REVIEW

Green building projects embody multiple technical disciplines with elevated levels of interdependency and interconnectedness as well as detailed requirements and specifications (Seyis, 2020). This makes design of green buildings much more complicated than conventional buildings. These issues result in various complexities and additional management challenges (Seyis, 2015; Seyis and Ergen, 2017). Efficient communication and continuous information flow between all disciplines are crucial to overcome such issues (Seyis, 2020). BIM provides an integrated digital platform to meet the requirements of green building projects by identifying any defect in the design of a facility that may prevent achieving the sustainability-related project objectives (Seyis, 2019).

Previous studies demonstrated that BIM ensures LEED-based sustainable design and construction (Solla *et al.*, 2019; Jalaei *et al.*, 2015) as BIM supports tracking green building certification process and selection of sustainable materials (Seyis, 2019). Accordingly, using BIM with its full potential in the green building project delivery process helps to decrease waste of time and cost related to the GBRSs (Seyis, 2019). One of the prominent previous studies on this subject domain showed that BIM-based tools are able to streamline the green building certification process (Azhar *et al.*, 2010). In this research, the performance of BIM-based tools (i.e., Autodesk Revit and IES-VE) were measured on the LEED v2.2 certification process (Azhar *et al.*, 2010). Similarly, in the study conducted by Raslan et al (2013) the impact of building energy simulation tools (i.e., Tas, EnergyPlus, IES-VE) were analyzed on the BREEAM v2011 and LEED v2009 certification processes. Similarly, Lu *et al.* (2017) addressed fourteen BIM software and their functions for LEED v3 based green buildings in order to analyze energy, carbon emissions, natural ventilation, daylighting and acoustics performance.

Another study performed a systematic literature review for evaluating contributions of BIM for four green building assessment systems including LEED, BREEAM, BEAM Plus and CASBEE (Comprehensive Assessment System for Built Environment Efficiency) (Ansah *et al.*, 2019). Doan *et al* (2017) investigated the usage of BIM tools for Green Star in New Zealand by performing literature review, semi-structured interviews and content analysis via NVivo 11. A BIM tool (i.e., Autodesk Revit) was used by Carvalho *et al.* (2019) for achieving the requirements of the Sustainable Building Tool in Portuguese.

In another research, a plug-in was developed for calculating and predicting the potential accumulated LEED v4 credits with access to the Application Programming Interface (API) of Autodesk Revit, Google Map and their associated library (Jalaei et al., 2020; Carvalho *et al.*, 2019). A comparable study used Dynamo BIM and API for fulfilling the requirements of Access to Quality Transit and Diverse Uses in LEED v4 (Li *et al.*, 2019). In more recent studies on LEED v4, a work was conducted on integrating health and well-being into the LEED v4 BD + C, and LEED v4 for Neighborhood Development (ND) rating systems (Jiang *et al.*, 2020); existing opportunities for population health promotion within LEED v4 was studied (Worden *et al.*, 2020); and the trade-off between time, cost, and sustainability was performed which were represented in terms of LEED v4 credits using a genetic algorithmic model (Kumar *et al.*, 2020).

Although there has been research on applying BIM-based tools in the area of green buildings over the last decade, only a few of the existing studies have examined the BIM-based tools for the different versions of LEED. To the knowledge of the authors none of these studies ave investigated the BIM-based energy analysis and design tools for use in the LEED v4 certification process in residential building projects. This research study analyzed the contributions of BIM-based energy analysis and design tools (i.e., Autodesk Revit GBS 2018, eQUEST v3.65, EnergyPlus v8.9, IES-VE 2018) to the LEED v4 credits in detail.

3. RESEARCH METHODOLOGY

The methodology of this study consists of the data collection and application steps. In the data collection step, a literature review was performed to integrate and criticize the previous studies on the subject domain. In the application step, a case study was conducted to gather in-depth information about the investigated topic.

3.1. Data collection

In the first step of this study, a literature review was performed using Web of Science and Scopus databases and publications that were published between 2008 and 2021 were investigated. Publications including any of the following keywords were identified: energy analysis software, energy analysis tool, energy analysis, BIM-based tools, BIM-based energy analysis, design tools, digital twins, and BIM software. Each publication was manually reviewed to select the appropriate data source. In total, 40 publications were investigated.

With this review, a total of 77 energy analysis tools were identified. Among these tools, only BIM-based tools were considered within the scope of the study, and the rest were eliminated. BIM-based tools, which are not (1) able to apply LEED credits, (2) up-to-date, (3) free access and/or have free trials, were eliminated. Finally, four BIM-based tools ((i.e., Autodesk Revit Green Building Studio, eQUEST, EnergyPlus, IES-VE) were selected to apply the LEED BD+C Multifamily Midrise rating system credits in this study. The selected tools are well-recognized tools that are commonly used and easily accessible to construction professionals.

3.2. Application

LEED was implemented in the case study because it is the most widely applied green building rating system around world (Kibert, 2016; Ansah *et al.*, 2019). More than 96,000 projects have been certified by LEED in over 165 countries (Stanley, 2016). Many building types such as residential, educational buildings, data centres, hospitals, retail buildings, warehouses, healthcare facilities, storage areas and distribution centres can be considered within the scope of the LEED rating system. Several prerequisites and optional credits should be accomplished to be able to earn the LEED certification for a building (Worden et al., 2020). For a project to receive LEED certification, first, the appropriate rating system should be selected. This should be followed by the selection of the proper credits for the project which are categorized under the preferred rating system. Finally, the requirements of these selected credits should be fulfilled by the interdisciplinary project teams during the execution of the project (Seyis, 2015; Seyis and Ergen, 2017). Overall, LEED is a well-accepted green building rating system as this leading standard is used for evaluating and reducing a building’s energy efficiency and carbon emissions (Kibert, 2016; Seyis and Ergen, 2017), and therefore selected to be investigated in this study.

LEED Building Design and Construction (BD+C) is selected as the rating system for the case study building since it is the rating system that is developed for buildings which are newly constructed or under major renovation. LEED v4 BD+C for Multifamily Midrise rating system, addressing four or more occupied stories above grade, was utilized in this study. The 3D model of the case study building was modeled in Autodesk Revit 2018 to be used in the investigation of the BIM-based tools for achieving the LEED v4 credits.

4. EVALUATING BIM-BASED TOOLS FOR LEED v4 BD+C: MM

A 6-floor residential building is used as the case study material performed within the scope of this study. This building is located in Istanbul, Turkey. Figure 1 shows the typical floor plan view and 3D view of the building that consists of two basement floors, a ground floor, three identical floors, an attic and a roof. Total construction area of the project is 1,793 m2 and the housing space is 1,024m2. The floor height is 2.9 m and the floor below the basement is used as a parking lot.

Figure 1:
the typical floor plan view and 3D view of the building in Revit

The 3D building model of the project was created in Autodesk Revit 2018. Modelling was performed by using the 2D .dwg files of the building, and the architectural and structural building components were included in the 3D model. Due to lack of related drawings, mechanical building components, fixtures and heating/cooling distribution systems were not included in the 3D model. Revit was preferred for the modelling of the case study building as it is a widely used and well-known BIM tool, and provides interoperability with other major tools. After modelling the case study building in Revit, the related 3D model was exported to the other three BIM-based tools (i.e., eQUEST, EnergyPlus, and IES-VE) to investigate the support of these tools in achieving the LEED credits for certification.

In LEED v4 BD+C MM, 46 credits are listed, and a project can collect a total of 110 points by achieving these credits. Based on the collected points, the project can be certified by LEED in one of the following categories: (1) Certified (40-49 points), (2) Silver (50-59 points), (3) Gold (60-79 points), and (4) Platinum (80+ points). By investigating the features of the selected BIM-based tools, applicability of each of the credits were examined for the case study building. Table 1 shows the credits that are achievable by using the selected BIM-based tools. During the examination of the LEED credits; related documents such as engineering references, manuals, application guides, input/output references and detailed simulation reports were utilized. Due to the different functionalities and divergent capabilities offered by each BIM-based tool, wide variety of measures were available. Features of these tools were analyzed to clarify how they can assist construction professionals in pursuit of the LEED certification process, and the findings are provided in the form of a comprehensive review that shows for which LEED credit category which energy analysis tool(s) can be used. Based on these findings, flowcharts were created that address the needs of various project team members who have different duties and responsibilities from design to the operation phases of projects. These flowcharts can be utilized as an aid during decision making with the intention of offering alternative solutions to ensure sustainability in every project stage.

Table 1. LEED v4 BD+C: MM achievable credits using four BIM-based tools

LEED v4 credits and maximum points		Revit	eQUEST	Energy Plus	IES-VE
Sustainable sites	Heat island reduction (2)	2	2	2	2
	Rainwater management (3)	3	0	3	3
	Nontoxic pest control (2)	½	0	0	½
Water efficiency	Water metering (P)	✓	✓	✓	-
	Minimum energy performance (P)	✓	-	-	✓
Energy and Atmosphere	Energy metering (P)	✓	✓	✓	✓
	Annual energy use (30)	30	0	30	30
	Efficient hot water distribution system (5)	5	5	3/5	3/5
Material and Resources	Advanced utility tracking (2)	2	2	2	2
	Environmentally preferable products (5)	5	5	5	5
	Combustion venting (P)	-	-	✓	-
Indoor Environmental Quality	Air filtering (P)	-	✓	-	✓
	Enhanced ventilation (3)	3	3	3	3
	Balancing of heating and cooling distribution systems (3)	3	1/3	1/3	1/3
	Enhanced combustion venting (2)	2	0	0	0
	Enhanced garage pollutant protection (1)	1	1	0	1
Regional Priority	Regional priority (N/A)	2	0	2	2
Total points		58 Points	18 Points	50 Points	52 Points

5. RESULTS

17 credits, including five prerequisites (i.e., 37 % of the total credits), can be performed completely or partially by using Revit GBS 2018, eQUEST v3.65, EnergyPlus v8.9 or IES-VE 2018. In terms of the total points obtained by the credits achieved, Revit seems to be the most successful tool with achieving 15 credits that equal to 58 points; while eQUEST may be considered as the least effective tool with only ten credits that correspond to a total of 18 points. However, a more detailed comparison that focuses on the special features of each tool is needed as provided in the following section. The results are presented in the form of flowcharts to assist in decision-making, and a table to demonstrate the capabilities of BIM-based tools in terms of project phases and intended users.

Four flowcharts were developed to assist various construction professionals in choosing a specific tool to be used in the LEED v4 certification process. In these flowcharts, “Re” refers to Autodesk Revit, “eQ” indicates eQUEST, “EP” points out EnergyPlus, and “I-V” stands for IES-VE. In each flowchart, the LEED v4 credits that correspond to the processes from the design until the operation phase were associated with the related BIM-based tools that are investigated. Although some parts show a few overlaps, the flowcharts were essentially prepared to represent the different perspectives of multiple parties involved in the construction processes. These parties include: (1) site execution team, (2) design team, (3) MEP (mechanical, electirical and plumbing) team, and (4) energy assessors and consultants who make decisions about LEED-compliancy and sustainable building designs using BIM-based tools.

Flowchart for the site execution team: This flowchart is aimed to be used by execution teams on site, such as contractors, field engineers and site managers. It focuses on the structural and mechanical tasks performed at site, and provides ideas on which BIM-based tools can be used during the execution of such tasks. If the 3D model of a building is readily available, structural works can easily proceed with collaboration and interoperability provided by the BIM-based tools. The 3D model of the building may not be available as working with 2D drawings is still the prevailing practice in the construction industry. In this case (i.e., if the 3D model is not available), first the 2D drawings are prepared, and then the 3D models are created based on these 2D drawings. Since all the tools investigated in this study are BIM-based, 3D model needs to be prepared using a BIM-based tool, such as Revit that was used in the modelling of the case study building.

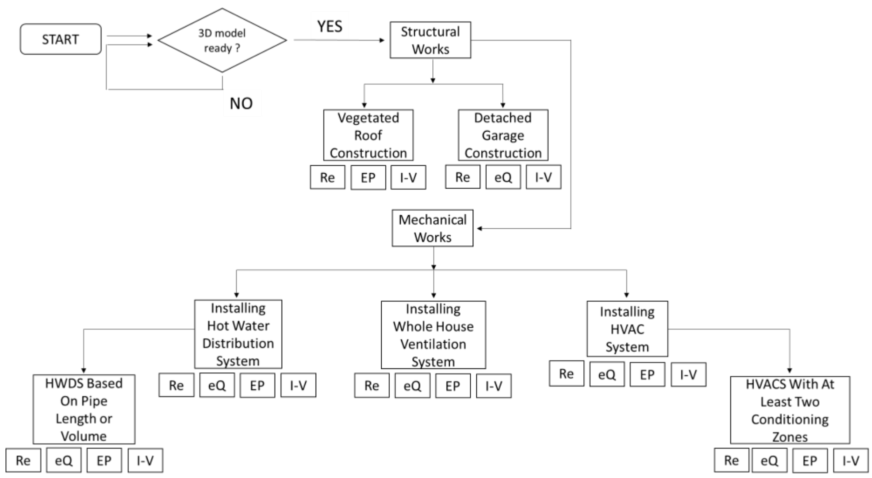

Figure 2:
Flowchart for site execution team

During the green roofing and garage construction, both Revit and IES-VE (Integrated Environmental Solutions-Virtual Environment) may be utilized. In addition, EnergyPlus and eQUEST can be advantageous for green roofing and garage construction, respectively. As for the mechanical works, contractors may be involved in the installation stages of HVAC systems and other mechanical systems, such as hot water distribution systems (HWDS) and whole house ventilation systems. Contractors would make the use of support of BIM during positioning and installation of such large and complex mechanical components. Each tool has features that may be utilized for multiple mechanical work processes, such as performing necessary calculations for the hot water distribution systems and installing a HVAC system with at least two conditioning zones.

Flowchart for the design team: This flowchart offers two paths to the users in the design phase (Fig. 3). If ASHRAE compliance is needed, the first option is to use the ASHRAE 62.2-2010 standard that is necessitated by the credits such as "Air Filtering" and "Enhanced Ventilation". eQUEST and IES-VE provide compliance for these standards. Second option is the ASHRAE 90.1-2010 standard that is demanded by the credits of "Minimum Energy Performance" and "Annual Energy Use". Revit and IES-VE provide assistance in complying with this standard.

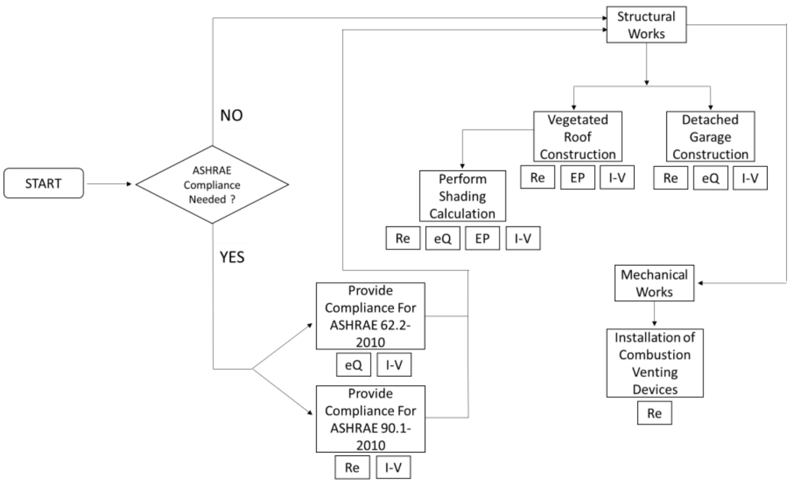

Figure 3:
Flowchart for design team

If ASHRAE compliance is not required or preferred (i.e., answer to the first question is "NO"), the flowchart proceeds with the construction phase, more specifically with the structural works. In addition to the structural works explained in the first flowchart (Fig. 2), green roof that improves the shading performance of the building can be created by designers. In this step, all four tools except eQUEST is helpful. All four tools (i.e., Revit, eQUEST, EnergyPlus and IES-VE) may be utilized for the shading calculations. Lastly, this flowchart shows that Revit can be used by the designers to perform modelling of the combustion venting devices in 3D during the mechanical works process (Fig. 2).

Flowchart for the Mechanical Electrical and Plumbing (MEP) team: Another flowchart was created to assist MEP team at certain stages of the mechanical works once the structural works are completed. These processes include installing mechanical building components and providing compliance for building energy assessment certifications (Fig. 4).

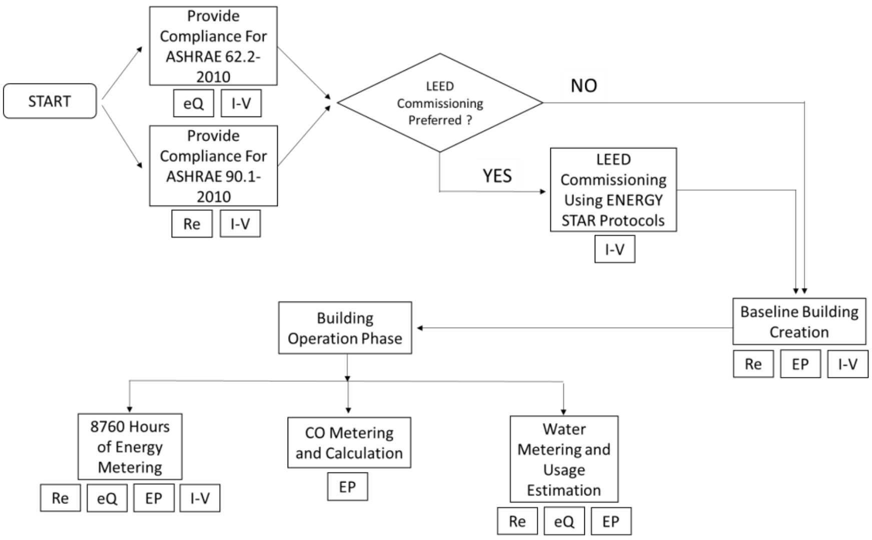

Figure 4:
Flowchart for MEP team

If the answer to the first question is “YES” (i.e., structural works are completed), the flowchart proceeds with the mechanical works. As it is stated in the first flowchart (Fig. 2), all four tools may be used during the installation of hot water distribution, whole house ventilation and HVAC systems. Three extra credits may be achieved by the MEP team using BIM-based tools related to these mechanical systems mentioned above. While both Revit and eQUEST may be used for adding insulations to pipes, and adding room-by-room thermostatic controls can be achieved only by using Revit. Additionally, MEP personnel can make use of eQUEST and IES-VE installing MERV air filter which is utilized for reducing allergens and providing an energy efficient HVAC system. MERV is designed by ASHRAE to measure the effectiveness of an air filter.

Flowchart for the energy assessors and LEED consultants: The last flowchart was designed to assist the energy assessors, LEED consultants or firms and/or individuals who offer green building certification system consultancy (Fig. 5).

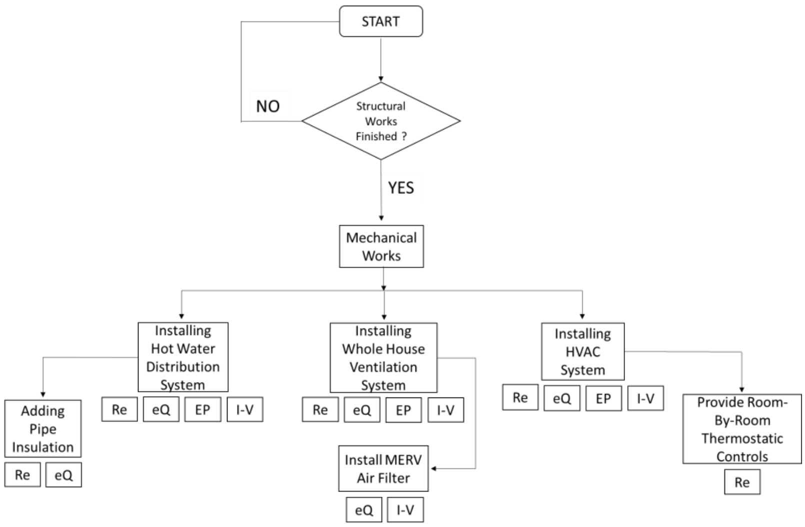

Figure 5:
Flowchart for energy assessors and consultants

Starting from the design phase, assuming that ASHRAE compliance is provided and further support is desired; commissioning may be preferred in pursuit of improving the energy efficiency of the design. IES-VE stands out as the only tool to offer LEED commissioning by fulfilling the ENERGY STAR protocols. Moreover, Revit, Energy Plus and IES-VE can be used to create a baseline building according to the ASHRAE standards that allows making comparisons considering the energy consumption benchmark. This helps understanding how the current design of the building performs, and assists in identifying the hotspots that need improvements in terms of energy consumption. Finally, the last step of the flowchart is related to the operation phase of the building. For the operation stage, hourly energy simulations during one-year period can be performed by all four tools. Yearly water metering and usage estimation is offered by Revit, eQUEST and EnergyPlus. On the other hand, only EnergyPlus provides CO metering and calculation at this stage. These features may be utilized by energy assessors with the purposes of measuring energy efficiency, suggesting the designers several ways to improve the building design and calculating the related cost.

Table 1 aggregates the information provided in the flowcharts. This table lists the capabilities of the BIM-based tools in terms of the LEED v4 credits based on the related project phases, and the intended users of the flowcharts, as described above. Project phases and the related credits are shown in the Table 2. The great majority of credits may be utilized by users of various roles, such as “Provide Compliance for ASHRAE 62.2-2010 / 90.1-2010” concerns designers, architects, energy assessors and consultants. To increase the support of BIM-based tools in the LEED certification process, more information regarding the building project must be collected, such as site layout and logistics.

Table 2. Capabilities of BIM-based tools and intended users based on project phases

Project Phase	Requirements	Revit	eQUEST	Energy Plus	IES-VE	Users
Design	Provide Compliance For ASHRAE 62.2-2010		✓	-	✓	D, EA&C
	Provide Compliance For ASHRAE 90.1-2010	✓	-	-	✓	D, EA&C
	LEED Commissioning		-	-	✓	EA&C
Construction	Installing Hot Water Distribution System	✓	✓	✓	✓	SET, MEP
	HWDS (Hot water distribution system) Based On Pipe Length or Volume	✓	✓	✓	✓	SET
	Adding Pipe insulation	✓	✓	-	-	MEP
	Installing Whole House Ventilation System	✓	✓	✓	✓	SET, MEP
	Installing HVAC System	✓	✓	✓	✓	SET, MEP
	HVACS With At Least Two Conditioning Zones	✓	✓	✓	✓	SET
	Provide Room-By-Room Thermostatic Controls	✓	-	-	-	MEP

	Installation of Combustion Venting Devices	✓	-	-	-	D
	Baseline Building Creation	✓	-	✓	✓	EA&C
	Detached Garage Construction	✓	✓	-	✓	SET, D
	Vegetated Roof Construction	✓	-	✓	✓	SET, D
	Perform Shading Calculation	✓	✓	✓	✓	D
	Install MERV Air Filter	-	✓	-	✓	MEP
Operation	8,760 Hours of Energy Metering	✓	✓	✓	✓	EA&C
	Water Metering and Usage Estimation	✓	✓	✓	-	EA&C
	CO Metering and Calculation	-	-	✓	-	EA&C

6. DISCUSSION

Application areas of BIM and 3D analysis tools are expanding in order to develop sustainable building designs according to the related standards (Muller, 2014). Findings of this study proved that BIM-based tools contribute to the LEED certification process and are helpful to construction professionals in developing sustainable and energy-efficient building designs. Revit resulted to be the most advantageous BIM-based tool by achieving more LEED credits than the other tools. However, this does not necessarily indicate that Revit is the most effective BIM-based tool among the four tools in terms of energy efficiency analyses. As the review of each BIM-based tool for the case study building, each tool has certain weaknesses and/or strengths from different environmental and performance aspects. An important finding of the investigation for the BIM-based tools in this study is that not a single BIM-based tool was able to achieve all the prerequisites and credits, and therefore, one viable solution can be to use Autodesk Revit for the modeling of a project and to complement its shortcomings with other tools, or with manual calculations.

One of the limitations of this study is related to using the educational version of IES-VE, which has some constraints in terms of energy analysis features; and therefore, only the LEED credits that were available with the educational version were examined. Also, EnergyPlus was not able to display the case study building created in Revit in 3D since it requires using other tools, such as SketchUp and OpenStudio, to be able to view the 3D model, and these tools were not used in the scope this study.

Another limitation was to model the case study building by only using the 2D structural and architectural drawings. Further information on the building's mechanical components, hardscape details and the finishing works were not available. Despite BIM-based tools being utilized in numerous fields, some LEED categories require further assistance such as the credits that necessitate achieving ENERGY STAR reference designs, checklists or testing and verification protocols (Energy Star, 2019). In some cases, certain credits (e.g., efficient hot water distribution system, balancing of heating and cooling distribution systems) could not be achieved completely due to limited data about the project. The same applies to the green building benchmarks and ASHRAE standards, as these could not be fulfilled when data is missing about certain details of the building, such as mechanical components. Therefore, examinations were limited on several credits of "Sustainable Sites" and "Indoor Environmental Quality" categories. If some requirements of a credit were fulfilled and the remaining requirements could not be achieved due to limited data; the credit was classified as "partially achieved.

7. CONCLUSIONS

This research demonstrates in what ways BIM-based energy analysis and design tools can support project teams in pursuit of LEED certification for residential buildings. Within the scope of this research, 77 energy analysis tools were reviewed, and Autodesk Revit Green Building Studio, eQUEST, EnergyPlus and IES-VE were selected to apply LEED v4 BD+C Multifamily Midrise rating system credits in the case study. The results of study contribute to the AEC industry and literature by providing (1) the pros and cons of these four energy analysis tools in terms of LEED v4 BD+C MM rating system credits, and (2) four decision-making flowcharts to be used as guidelines by the AEC professionals. These include site execution teams, design teams, MEP teams, and energy assessors and consultants who would want to effectively conduct BIM-based LEED certification process, and design more energy-efficient buildings. Further, these flowcharts add value to the AEC industry and literature because none of the previous studies developed such a guideline for using BIM-based tools with the aim of assisting decision makers in the LEED v4 based sustainable design and construction.

The results of this research show that a total of 17 LEED v4 BD+C MM credits including five prerequisites (i.e., 37 % of the total credits) can be performed completely or partially by Autodesk Revit GBS 2018, IES-VE 2018, EnergyPlus v8.9 or eQUEST v3.65. In the LEED v4 BD+C MM rating system, 18, 50, 52 and 58 points out of 100 points can be achieved by eQUEST, EnergyPlus, IES-VE and Autodesk Revit GBS, respectively. These results prove that Autodesk Revit GBS 2018 is much more useful and successful than eQUEST, EnergyPlus and IES-VE in terms of fulfilling the requirements of LEED v4 BD+C MM rating system credits. Contrary to this, eQUEST may be considered as the least effective tool in the LEED-based sustainable construction projects, although each tool having certain strengths and weaknesses. More importantly, all the prerequisites and credits cannot be fulfilled by a single BIM-based tool. Hence, this issue can be solved using Autodesk Revit for the modeling of a project and achieving its shortcomings with other tools, or with manual calculations.

The other primary results of this study is four decision-making flowcharts that can support the integrated use of BIM and LEED v4 in the residential building design. The first flowchart developed for assisting the site execution teams focuses on the structural and mechanical tasks performed at site, and provides ideas on which BIM-based tools can be used during the execution of such tasks. The second flowchart developed for assisting the design teams shows that Revit can be used by the designers to perform modelling of the combustion venting devices in 3D during the mechanical works process. The third flowchart developed for assisting the MEP teams focuses on installing mechanical building components, and use of BIM-based tools for providing compliance for building energy assessment certifications. Finally, the fourth flowchart developed for assisting the consultants and/or energy assessors in order to measure energy efficiency, improve the building design and calculate the related cost with the help of BIM-based tools.

The limitations of this study can be summarized as using the educational version of one of the investigated tools (i.e., IES-VE), creating the 3D model based on the 2D structural and architectural drawings without the use of MEP drawings, and not considering the costs of the LEED credits. The scope of this research is limited in the “Sustainable Sites” and “Indoor Environmental Quality” categories due to the lack of MEP drawings for the case study building.

One of the future works would be developing additional decision making flowcharts for the new versions (i.e., LEED v4.1) and other rating systems (e.g., Operation and Maintenance) of LEED, and different building types (e.g., hospitals, schools, office buildings). Another future direction could be to include the cost aspect within the scope of this research.

CONFLICT OF INTEREST

Author(s) approve that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

AUTHOR CONTRIBUTION

Senem Seyis and Gursans Guven contribute to determining the concept and/or design process of the research, management of the concept and/or design process of the research, preparation of the manuscript, critical analysis of the intellectual content, final approval and full responsibility. Berkant Bayar contributes to data collection, data analysis and interpretation of the results.

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