A REVIEW OF BIM-BASED ENERGY ANALYSIS TOOLS FOR LEED CERTIFICATION PROCESS

A Thesis

by

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Submitted to the

Graduate School of Sciences and Engineering
In Partial Fulfillment of the Requirements for
the Degree of

Master of Science

in the
Department of Civil Engineering

Özyeğin University
January 2020

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A REVIEW OF BIM-BASED ENERGY ANALYSIS TOOLS FOR LEED CERTIFICATION PROCESS

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To My Love & My Family,

ABSTRACT

In the recent years, there has been a growing interest among designers and owners to use systems developed to assess building performance with the intention of achieving sustainability in the construction industry. Estimating the energy performance of buildings and calculating the related costs necessitate using a standardized method for measurement. To serve this purpose, green building rating and certification systems (GBRCSs) have been established to assist construction professionals in developing designs with better energy performances by having insights on the building energy consumption characteristics. GBRCSs reward relative levels of building performance with specific environmental goals and requirements. The world's most widely used GBRCS is the Leadership in Energy & Environmental Design (LEED) developed by the United States Green Building Council (USGBS). Therefore, this study aims to investigate the extent to which Building Information Modelling (BIM)-based energy analysis and design tools can assist the construction professionals in the certification process of LEED. The goal of this thesis is to demonstrate in what ways BIM-based energy analysis and design tools can support construction project teams in pursuit of LEED certification for their projects. To achieve this objective, a residential building is modelled in Autodesk Revit and then exported to three other BIM-based energy analysis tools, namely eQUEST, EnergyPlus and Integrated Environmental Solutions – Virtual Environment (IES-VE). Applicability of LEED v4 'Building Design and Construction (BD+C): Multifamily Midrise' credits are examined through detailed investigation of the features of the four abovementioned BIM-based tools. Based on the findings of this study, flowcharts are developed to help project participants to make better decisions on how to use BIM-based tools in LEED processes that aim to construct more energy efficient

buildings. Also, the findings are useful in understanding how to use these tools to achieve higher scores in green building certification processes of the LEED.

ÖZETÇE

Son yıllarda inşaat sektöründe sürdürülebilirliği sağlamak amacıyla, tasarımcılar ve mal sahipleri arasında bina performansını değerlendirmek için geliştirilen sistemlerin kullanımına olan ilgi artmıştır. Binaların enerji performansının ve ilgili maliyetlerin tahmininin yapılabilmesi, standart hale getirilmiş ölçüm metotlarının kullanılmasını gerekli kılmaktadır. Bu amaca hizmet etmek için, yeşil bina sınıflandırma ve sertifikasyon sistemleri inşaat sektörü çalışanlarının binaların enerji tüketim karakteristikleri hakkında bilgi sahibi olarak daha iyi performansa sahip tasarımlar ortaya koyabilmeleri niyetiyle kurulmuştur. Dünyada en yaygın kullanılan yeşil bina sınıflandırma ve sertifikasyon sistemi, Amerikan Yeşil Binalar Konseyi (USGBC) tarafından kurulan Leadership in Energy and Environmental Design (LEED)'dır. Buna bağlı olarak, bu çalışma Yapı Bilgi Modellemesi (BIM)-tabanlı enerji analizi ve tasarım araçlarının inşaat sektörü çalışanlarına LEED sertifikasyon sistemi sürecinde ne derece destek olabileceğini araştırmayı hedeflemektedir. Bu tezin amacı, BIM-tabanlı enerji analizi ve tasarım araçlarının inşaat projelerinin LEED sertifikasyonu almasında proje ekiplerine ne şekilde destek olabileceğini göstermektir. Bu hedef doğrultusunda, bir konut projesi Autodesk Revit kullanılarak modellenmiş ve sonrasında üç adet daha BIM-tabanlı yazılıma (eQUEST, EnergyPlus ve Integrated Environmental Solutions – Virtual Environment (IES-VE)) aktarılmıştır. LEED v4 "Bina Tasarım + İnşaat (BD+C): Orta Yükseklikte Bina (Multifamily Midrise)" kredilerinin uygulanabilirliği yukarıda bahsedilen dört BIM-tabanlı aracın detaylı araştırılması yoluyla incelenmiştir. Bu çalışmanın sonuçları ışığında, proje paydaşlarının enerji tasarruflu binalar inşa edilmesini amaçlayan sürdürülebilir bina tasarım süreçlerinde BIM-tabanlı yazılımları nasıl kullanabileceklerine dair kararlar vermelerine yardımcı olacak akış şemaları

oluşturulmuştur. Çalışmanın sonuçları ayrıca, BIM-tabanlı yazılımların LEED yeşil bina sertifikasyon sürecinde daha yüksek skorlar edebilmek için nasıl kullanılabileceği konusunda bilgi sunmaktadır.

ACKNOWLEDGMENT

I would like to express my deepest gratitude to my thesis advisor Asst. Prof. Dr. Gürşans Güven Işın, and my thesis co-advisor Asst. Prof. Dr. Senem Seyis Kazazoğlu for their guidance, patience and endless support. I would like to thank my advisor especially for her friendliness from the very beginning of my graduate journey. I would like to thank Asst. Prof. Dr. Zeynep Başaran Bundur, Asst. Prof. Dr. Taner Yılmaz, and Asst. Prof. Dr. Sevilay Demirkesen Çakır, for accepting to be in my thesis committee, and for their valuable feedback. I would like to appreciate all faculty members of Ozyegin University, Civil Engineering Department for their contributions and mentorship throughout my undergraduate and graduate education.

I would like to acknowledge all employees of Ozyegin University for their co-operation and assistance during my seven years in this university. At this point, I would like to especially thank to Gizem Bakır and Mehtap Yıldırım for their assistance, support and tolerance.

Lastly, I would like to express my special gratitude to my friends Gökhan Tekbaş, Onur Cem Aygın, and Cem Demirci. I would like to thank my friend Gökhan Tekbaş for his fellowship and endless support, my friend Onur Cem Aygın for his smiling face and trustworthiness, and my friend Cem Demirci for his friendship and contribution during my thesis study. Finally, I would like to thank my girlfriend Özge Yaltı for her patience, reliance and deepest love.

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ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
AEC	: Architecture, Engineering and Construction
ASHRAE	: American Society of Heating Refrigerating and Air Conditioning Engineers
BD+C	: Building Design and Construction
BIM	: Building Information Modeling
BREEAM	: Building Research and Establishment Environmental Assessment Method
CSB	: Case Study Building
GBAS	: Green Building Assessment Scheme
GBRCS	: Green Building Rating and Certification Systems
GBS	: Green Building Studio
GHG	: Green-House Gas
HVAC	: Heating, ventilation and air conditioning
IES-VE	: Integrated Environmental Solutions – Virtual Environment
LEED	: Leadership in Energy and Environmental Design
MEP	: Mechanical, Electrical and Plumbing
MERV	: Minimum Efficiency Reporting Value
MM	: Multifamily Midrise

NC	: New Construction
USGBC	: United States Green Building Council

CHAPTER I

INTRODUCTION

The concept of sustainability has been much-discussed for decades from different perspectives regarding the effects on human lives and nature. Growing concerns of environmental damages and waste management, together with the issues of climate crisis, make this topic broadly acknowledged. Our planet Earth is facing serious threats such as excessive amount of raw material consumption, global warming through climate change, production of green-house gas (GHG) emissions, depletion of natural resources, gradual increase in poverty, and so on (Rukikaire and Lopez 2019). Moreover, the pressure on the nature with further population growth could also lead to social impacts of sustainability. Increase in poverty is currently a threat for future considering the high-level of population growth. Statistics show the severity of the current situation, and unfortunately, the future of the world seems desperate at this point. One of the most significant figures is about the management of solid waste. Numbers state that in 2016, amount of solid waste generated by cities increased to 2.01 billion tonnes which is equivalent to 0.74 kilograms per person per day (The World Bank 2019). Previous studies indicate that construction industry is one of the largest contributors to GHG emissions, and therefore, responsible for a dramatic level of natural resource consumption (Kibert 2016). It has been stated that construction industry is responsible for up to 30% of global annual GHG, and 31% of all the waste generated (Roser 2017). Reducing raw material consumption and ensuring more renewable material usage is intended to reduce carbon footprints. Furthermore, "*natural resource consumption in the* *construction industry has increased 80% since 1980 compared to a 60% increase in overall resource consumption*", according to the Organization for Economic Co-operation and Development (OECD) (Redmond 2016).

Economic aspects of sustainability should also be considered as well as its environmental and social impacts. According to the research performed by Coelho et al. (2013), around 1.13 million Euros are spent for transportation of waste material, while another 10.3 million Euros for their dumping process in landfills. There have been some studies to reduce waste generation. In one study carried out by Barratt Developments PLC in East Yorkshire, waste generation was reduced 10% in 2017 compared to the baseline figures of 2015 (Partridge 2018). While 15,000 tonne waste was reduced, £850,000 was saved through the waste management cost (Partridge 2018). Accordingly, achieving sustainability in the construction industry is crucial for solving environmental problems, and also, saving money to a certain extent.

With the aim of fulfilling the requirements of sustainability in construction projects, planning and design phase gained importance thanks to the contribution of computer-based energy analysis tools. Use of digital support during the design phase potentially minimizes the amount of manual calculations and saves time in most of the cases. Many design changes can be applied and analysed through detailed simulations for different scenarios. Tools that allow designing green buildings with environmentally friendly materials can help create more sustainable built environment, and consequently promote sustainable development while supporting the economy (Mackey 2019). Architecture, engineering and construction (AEC) industry professionals put emphasis on performing energy measurements for buildings by utilizing Building Information Modelling (BIM)-based tools. BIM enables three-dimensional digital representation of a building and all its processes (Sacks et al., 2018). BIM-based energy analysis and design tools (i.e., interchangeably used as "BIM-based tools" in the thesis) are developed to support green construction, help reducing carbon footprint and therefore creating better environmental solutions while minimizing the cost (Wong and Fan 2013). A green building or sustainable building reduces negative impacts in its construction, operation phases and affect natural environment positively (Umar, et al. 2012). Green buildings: (1) use renewable energy, (2) enable re-use and recycling, (3) consider the quality of life for occupants and (4) reduce excessive waste (Nicasio 2012). Green buildings are environmentally responsible and resource-efficient throughout their life cycle and that in turn decrease solid waste, increase quality of life and preserve natural resources (Lu, et al. 2017). Therefore, the more sustainable solutions are applied, the less impact of construction industry on the natural environment can be achieved. Hence, promoting sustainability in the AEC industry plays a significant role in constructing a better life for future generations.

In order to design and construct green buildings as well as promoting a sustainable built environment; construction professionals started to use building performance assessment systems over the last decades. Calculating the energy performance and the cost of buildings necessitate using a standardized method for measurement (Burman, et al. 2014). Building performance assessment systems enable performing quantitative measures that are necessary for a green building construction. A standardized methodology is required for conducting the energy performance analysis and cost estimations in an effective manner (Burman, et al. 2014). Hence, the Green Building Rating and Certification Systems (GBRCSs) are developed to assist professionals measuring the building performance and fulfilling the sustainability requirements. GBRCSs reward relative levels of building performance with specific environmental goals and requirements (Vierra 2019). Most of the GBRCSs have similar purposes such as verifying environmental performance of buildings, using natural resources efficiently, estimating and forecasting the energy performance of buildings in terms of different aspects and encouraging more energy-efficient building designs. Measuring the energy performance of buildings using GBRCSs could help reducing excessive waste and promoting sustainability in construction.

1.1. Objective of the Thesis

The first objective of this thesis is to investigate the support of BIM-based energy analysis and design tools during the LEED certification process. Second objective is to create flowcharts that can be used by various project participants for deciding which tool to use for what specific purposes during the LEED process. It is aimed to introduce how BIM can enhance the sustainable construction processes, and eventually, to encourage the construction professionals to use BIM. The goal of this thesis is to demonstrate in what ways BIM-based energy analysis and design tools can support construction project teams in pursuit of LEED certification for their projects. Although these tools are mainly developed for energy analysis and referred to as energy analysis and design tools throughout this thesis, the focus of this thesis is to investigate the support of these tools during the LEED certification process and calculation of LEED credits. Therefore, it is not the objective of this study to perform energy analysis using these tools. It should be noted that the requirements of LEED credits include not only focuses on energy related features of buildings, but also it is concerned with the structural and mechanical aspects of projects.

1.2. Scope of the Thesis

LEED is selected as the GBRCS to be investigated within the scope of this thesis since it is globally one of the most widely used and well-known systems (Kibert 2016). LEED is one of the most widely used GBRCSs around the world along with Building Research Establishment Environmental Assessment Method (BREEAM). They have different perspectives and certification processes. The main reason why LEED is examined in this thesis is that it requires more calculations to be performed to achieve a certain level of certification (Rezaallah, et al. 2012). Additionally, project team is responsible for preparing the necessary documentation throughout the LEED certification process. As for BREEAM, an assessor is responsible for inspecting the fulfilment of requirements and for reporting (Vecchio 2016). Therefore, it is useful for the project teams to utilize tools that can help with the calculations and documentation necessary for the LEED processes. LEED v4 is adapted in this study, and the applicability of LEED v4 'Building Design and Construction (BD+C): Multifamily Midrise' credits are examined. Credits included in the "Location and Transportation" category are out of scope of this thesis because this category requires performing a detailed data collection and comprehensive studies on the logistics of the building. In addition, "Integrative Process" and "Innovation" category that have qualitative credits are left out of the scope of this thesis.

There are many energy analysis and design tools available in the market to help project teams with calculating building energy performance and to create energy-efficient designs. Since BIM provides the 3D digital representation of a building and all its processes, BIM-based tools can be used to perform both energy analysis and design, and therefore, useful in the process of LEED certification. However, it is difficult for the project teams to decide which specific tool to use for what purpose and for which credits of LEED. Four BIM-based tools are utilized within the scope of this study to investigate to what extent these tools can be helpful in LEED certification processes. Selected BIM-based tools are compatible with Autodesk Revit. Cost analysis was not included when examining the LEED credits and any other monetary concept is left out of the scope.

1.3. Plan of the Thesis

This thesis study consists of seven chapters. Chapter 1 defines the research problem and presents the objective of this thesis. In addition, scope and plan of the thesis are included in this chapter. Chapter 2 explains the methodology and the approach of the thesis. In Chapter 3, the review of the related literature is presented to discuss the purposes of former studies and their contributions and present ideas for improvements. Chapter 4 presents the case study, along with the LEED work plan, rating system selection, explanations of energy analysis tools, and the requirements of the LEED credits. Results of the thesis are given in Chapter 5. Areas of usage for energy analysis tools and their support to LEED certification system process are further discussed. In Chapter 6, comparison of the energy analysis tools is discussed, their pros and cons compared to each other are described, and the limitations of the thesis are presented. Finally, in Chapter 7, conclusions of the study along with its contributions, implications and recommendations, and future work are provided.

CHAPTER II

LITERATURE REVIEW

2.1. LEED

With the intention of creating green buildings and achieving sustainability in the AEC industry, practitioners typically give a great deal of importance to building design in the early stages of a project. The need for estimating the energy performance along with the necessary cost analysis, led the way to develop more standardized measurement techniques. This way, assessment systems for green buildings have started to take part in the market. Many countries have launched their national GBRCSs to support design and construction of green buildings. Currently, BREEAM and LEED are currently accepted as the two most widely used rating systems (Bernardi, et al. 2017). BREEAM from the United Kingdom is one of the first and mostly used GBRCS that was established in 1990 with certification levels of “pass”, “good”, “very good”, “excellent” and “outstanding” (McPartland 2016). LEED was developed by the United States Green Building Council (USGBC) in 1998. More than 96,000 projects have been certified by LEED worldwide in over 165 countries (Stanley 2019). Many building types such as residential, educational buildings, data centres, hospitals, retail buildings, warehouses, healthcare facilities, storage areas and distribution centres may be the subject of a LEED certification. LEED-certified buildings aim to save energy and water, reduce waste, increase productivity and protect human health. Latest version (v4) of LEED was released in 2013, and it is the version that is utilized in this thesis. Version 4 has nine main categories for green building measurements, namely: Integrative Process, Location and Transportation, Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, Innovation and Regional Priority. In order to receive the certificate, after choosing the most appropriate rating system for the project and completing other paper works; requirements of credits must be fulfilled. Each credit means points, and based on the number of points obtained, a project can qualify for one of four different certifications, namely: Platinum, Gold, Silver or Certified.

2.2. Other Commonly Used Green Building Rating and Certification Systems

Among other major GBRCSs, there is ENERGY STAR that started as a government certification system in the United States in 1992 (Vierra 2019). Also, BEAM PLUS from Hong Kong was introduced in the late 90s and reached 1,000 registered projects in 2017. (Vierra 2019). In the early 2000s, Green Globes from Canada which has now more than 3,300 certified buildings was established (Vierra 2019). CASBEE from Japan and Australia's Green Star are also well-known GBRCSs in their regions (Doan, et al. 2017). Lastly, GREEN MARK from Singapore was launched in 2005 and is considered as one of the latest acknowledged certification systems (Vierra 2019).

2.3. Previous Related Studies

In this section, studies that were published in between the years 2008 to 2019 were reviewed. Researchers have been working on improving the connection of BIM and green buildings over the last couple of years. In a research conducted by Lu, et al. (2017), a reflection on the relationship between BIM and green buildings was presented. Within the scope of that study, an older version of LEED (i.e., LEED v3) was used for the examination of the credits (Lu, et al. 2017). Several widely used BIM-based tools were examined in terms of BIM applications that support green development in various project phases. Twelve BIM-based tools and their functions were demonstrated for multiple types of green analyses such as energy, carbon emissions, natural ventilation, daylighting and acoustics. BIM-supported assessments of GBRCS were explained in a table format that include six credit categories and four different GBRCSs (i.e., LEED, BREEAM, Green Star, BEAM Plus). Lastly, several research gaps were identified revealing the weak interoperability among different BIM applications, low industrial acceptance of BIM and lack of standard industrial codes (Lu, et al. 2017).

In one of the earlier studies, a comparison of LEED versions and different versions of The American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) standards were made (Rastogi, et al. 2017). In that study, different scenarios were analysed to find the most optimal combination. This study aimed to explain the differences between the LEED versions in terms of credit requirements and the applied scoring system. Percentages of energy performance improvements were indicated with graphical demonstrations that include energy consumption categories such as lighting, space heating, space cooling, heat rejection, etc. Major limitation of this study was that it only considered the energy and atmosphere (EA) category (Rastogi, et al. 2017).

In a former study performed by Azhar, et al. (2010), LEED v2.2 credits were evaluated by the contribution of BIM-based tools. This study dealt with a case study building in order to demonstrate the benefits of BIM in sustainable building design including the

LEED certification process. Main purpose of the study was to show that BIM could be utilized for various sustainability measures during the LEED v2.2 certification process. Without investigating the financial outcomes, a non-residential building was used to show the relationship between BIM and LEED. Credits of LEED – NC (New Construction) that can be earned by using BIM-based tools such as Autodesk Revit and Integrated Environmental Solutions - Virtual Environment (IES-VE) were shown (Azhar, et al. 2010). Based on the sustainability analysis and the research on BIM-based tools (i.e., Autodesk Revit and IES-VE), 17 LEED credits and two prerequisites that worth 38 points were achieved. Results indicated that BIM-based tools can streamline the green building certification process through their sustainability-related analysis techniques.

In another related work, Schwartz and Raslan (2013) performed a research on how building energy simulation tools can have an impact on the BREEAM and LEED certification process. In the study conducted by Schwartz and Raslan (2013), versions of 2011 for BREEAM and 2009 for LEED were used for comparison. Purpose of that study was to examine the variations in the results generated by three most widely used energy analysis tools (i.e., Tas, EnergyPlus, IES-VE), and figure out their influence on overall scores of BREEAM and LEED (Schwartz and Raslan 2013). 8,760 hours of building operation was simulated for annual energy use. Also, the total energy consumption in terms of heating and cooling rates were demonstrated according to the simulation results of these three tools. Findings of this study show that different simulation tools produced various energy usage figures, however, they had minor effects on the credit scores of the two rating systems. Nonetheless, the results showed that the case study building qualified for a quite different rating level since the assessment procedures of BREEAM and LEED are different from each other (Schwartz and Raslan 2013).

In one of the most recent studies conducted by Ansah, et al. (2019), a systematic review on the contribution of BIM for the use of Green Building Assessment Schemes (GBAS) was presented. Benefits of four GBASs (i.e., LEED, BREEAM, BEAM Plus and CASBEE) that are being practiced worldwide were demonstrated through reviewing comprehensive databases. Several BIM-based tools were selected, and previous studies were reviewed (Ansah, et al. 2019). Based on the presented results of a survey in this study, “Innovation” criteria, although being a qualitative criterion, is also stated as can be satisfied by BIM. Findings of this study showed that LEED identified as the most widely used GBAS. References of applying BIM to green building design processes were provided for researchers.

Another recent study by Li, et al. (2019) introduced the method of custom coding for LEED v4 assessments. The authors utilized the visual programming tool Dynamo for scripting, and the Application Programming Interface (API) to connect two applications to fulfil the requirements of location-related credits of LEED. More specifically, they presented the coding and simulation methods for validating the “Quality Transit” and “Diverse Uses” assessment criteria of LEED. Dynamo was used to set the project location, and the project address, shortest walking range and walking path were shown in different colours. This study presented how to retrieve data using Dynamo for specifying the project location and finding site surroundings.

Literature review demonstrated that although there are several previous studies that mainly focused on using the energy analysis tools in case studies, only a few studies were conducted to examine the credit information and requirements of LEED in detail. Also, the previous studies were conducted with the older versions of LEED. Moreover, the support of BIM-based energy analysis and design tools in the LEED processes and for achieving LEED credits have not been investigated in detail for the most recent version of the LEED.

2.4 BIM-Based Energy Analysis Tools

Another literature review was performed to identify the existing BIM-based tools in the market. The following keywords were used: “energy analysis software”, “energy analysis tool”, “energy analysis”, “BIM-based tools” and “BIM software” to search the databases such as American Society of Civil Engineering (ASCE) Library (https://www.asce.org) and ScienceDirect (https://www.sciencedirect.com). Initially, 77 energy analysis tools were identified. Among these, BIM-based tools were considered, while the rest was eliminated. Some of the identified tools were found irrelevant due to having features that are not necessarily applicable to LEED credits, and due to measuring electric bills or regulating the water treatment works. Some outdated tools were also eliminated. These tools were not up to date, and in some cases, the latest updates of were published almost 10 years ago. After these eliminations, number of available energy analysis tools were down to 33. Still, there were many energy analysis tools to be dealt with and further elimination was required.

Among these, only the ones that provide free access and/or free trials were used and this dropped the number of BIM-based tools to eight. Finally, after facing some technical issues during the installation step and due to time limitations, four tools were selected to be used in this thesis. While three of them are free of charge (i.e., Autodesk Revit, eQUEST, EnergyPlus), one-year student license was purchased for IES-VE. The student version of

IES-VE has some limitations in terms of energy analysis features, and because of that, only the LEED credits that were available with the student version were examined. Next section describes the methodology on how the case study was developed and how the selected tools were applied in this thesis.

CHAPTER III

METHODOLOGY

Methodology followed throughout this thesis is demonstrated in Figure 3.1. In order to achieve the research objectives, first a literature review was conducted (Figure 3.1-a). In the literature review as presented in the previous chapter, related studies conducted earlier were reviewed, and a detailed research on the existing energy analysis tools was performed to select the BIM-based tools that are used in this study (Figure 3.1-b). The selected tools are Autodesk Revit, eQUEST, EnergyPlus, and IES-VE. Then, a case study was conducted (Figure 3.1-c) with the intention of practicing and examining the features of the energy analysis tools in detail (Figure 3.1-d).

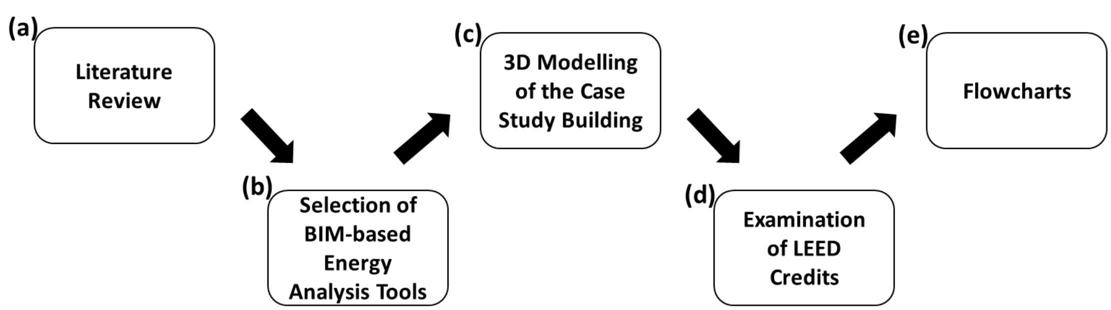


Figure 3.1 Methodology followed in this thesis

The case study (Figure 3.1-c and Figure 3.1-d) conducted in this thesis includes three steps: (1) 3D modelling of the building, (2) investigation of LEED credits in Autodesk Revit, and (3) exporting the Autodesk Revit model to the other three tools for further investigation of the LEED credits. As the first step, 3D model of the case study building was created in Autodesk Revit 2018 by using the two-dimensional (2D) Autodesk AutoCAD (.dwg) drawings. Main reason of using Autodesk Revit for the modelling was that it is a widely used and well-known BIM tool, and provides interoperability with other major tools. The created model includes architectural and structural components, and the LEED credits and their requirements were examined firstly by using Autodesk Revit. This building model was then exported to other three BIM-based tools (i.e., eQUEST, EnergyPlus, and IES-VE).

After the completion of the 3D model in Revit, LEED work plan was summarized to clarify the main tasks included in the LEED certification process (Figure 3.1-d). Following this step, the rating system that is used in this thesis was selected for the case study building. All explanations and calculations were done based on the selected rating system. A brief information on the requirements of LEED credits is also given in the thesis to guide the reader regarding the general procedure. As the next step, LEED credits were examined in detail firstly by using Revit. For this purpose, Revit's Green Building Studio (GBS) add-in was utilized to analyse the building performance in terms of energy, water, carbon footprint, fuel, utilities and cost. Green Building Studio is a cloud-based service that enables running building performance simulations with the intention of optimizing energy efficiency (Ofluoglu, 2016). LEED credits were examined to determine how many of them can be achieved completely or partially with the related features of Revit.

Examination of the LEED credits continued with exporting the 3D Revit model to eQUEST, EnergyPlus and IES-VE, respectively (Figure 3.1-d). During the examination of the LEED credits, introductory documents of these tools 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 sustainability measures were available. Features of these tools were analysed to clarify how they can assist construction professionals in pursuit of the LEED certification process. 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 the findings, flowcharts were created (Figure 3.1-e) that address the needs of various project participants 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.

The weaknesses and strengths of the BIM-based tools used in this study compared to each other were stated in the discussion section in terms of applicability of several LEED credits. Some credits that can be fulfilled by all tools were not included in this comparison as it would not be possible in that case to make a distinction on which tool is more advantageous. Also, the significance of the results and the limitations of this study are presented in the discussion section. Finally, in the last chapter, general outcomes of the thesis, contributions and the related future work were explained.

CHAPTER IV

CASE STUDY

4.1. 3D Modelling of the Case Study Building

In the modelling part of the study, Autodesk Revit 2018 was utilized for designing the 3D building model of a residential building. Modelling in Revit was performed by using the 2D .dwg files and architectural and structural building components were included in the 3D building model. Mechanical, electrical and plumbing (MEP) components, such as mechanical building components, fixtures and heating/cooling distribution systems, were not included due to lack of related drawings and lack of modelling experience in the MEP discipline. The case study building is a six-storey residential building that is located in Istanbul, Turkey. As shown in Figure 4.1(a), the building 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 m^2 and the housing space is 1,024m^2. The floor height is 2.9 m and the floor below the basement is used as a parking lot. Plan view of an identical floor is given in Figure 4.1(b).

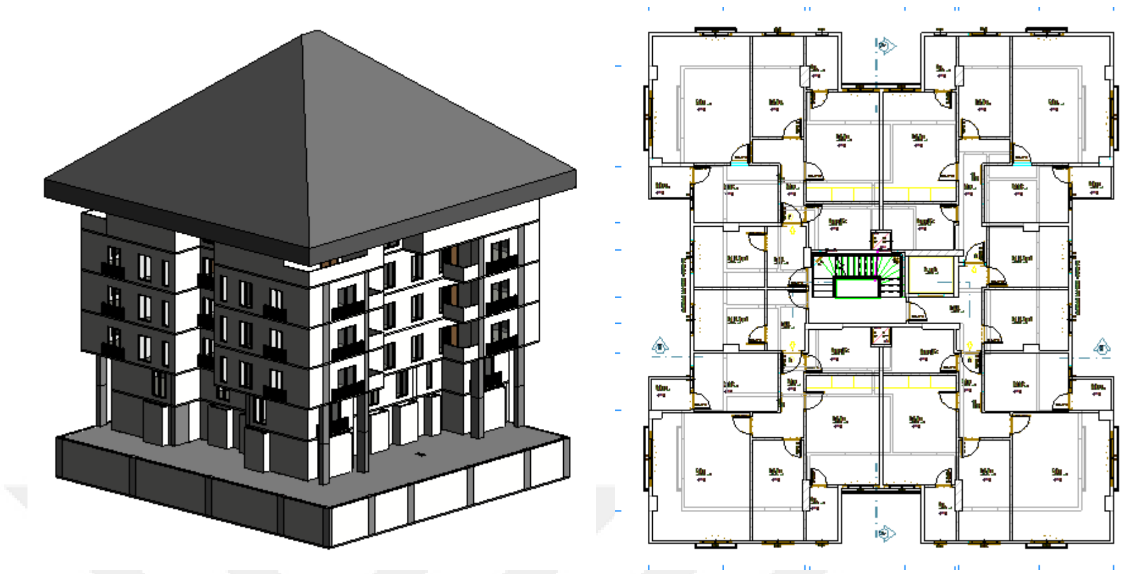


Figure 4.1 (a) 3D model of the case study building created in Autodesk Revit 2018, and (b) identical floor plan

4.2. LEED Work Plan

LEED certification process requires to follow multiple tasks from the beginning until the end. A project team must follow several instructions to be able to become LEED-certified. The main tasks allocated to the project team are: (1) to choose the rating system type, (2) to target the desired score, (3) to provide consistent documentation, and (4) to review for the final inspection. Before continuing with the case study building and investigations on the energy analysis tools, brief explanation of these early tasks are given to demonstrate the whole process.

In the first step, appropriate rating system is determined based on the building type or phase and the owner's project requirements and the project should be checked whether it has the minimum characteristic or not. These characteristics are as follows: (1) buildings should be in a permanent location on an existing land, (2) should use reasonable LEED boundaries, and (3) the size requirements should comply with the standards (USGBC 2014).

Second step is to identify the desired LEED rating level and to assign roles to project team members accordingly after the project scope is defined. At this point, a LEED Green Building Consultant (Benjamin 2019) can guide the project team in taking the right steps.

Third step requires to consistently provide documents that consists of plans, drawings, calculations, photographs and other important details during the construction by a team member who is responsible for the LEED certification process. Project data should be recorded regularly, and informative meetings should be conducted with the Green Building Consultant to track the progress.

Lastly, through site inspections, verification of the credits and review of the documentation, the project qualifies for the last examination. If the Green Building Consultant confirms the process, project is submitted to the USGBC for certification review.

4.3. Selection of the LEED Rating System

In this study, LEED's rating system of "Building Design and Construction (BD+C)" is selected, since it was developed for buildings that are newly constructed or under major renovation. According to the LEED standards, the case study building used in the project is classified in the "Multifamily Midrise (MM)" section that applies to four or more occupied stories above grade. For LEED BD+C Multifamily Midrise projects, 46 credits are listed in v4. The credit names and possible points that can be obtained from each credit are given with detailed explanations in the credit investigations part. A total of 110 points can be collected in the rating system of LEED BD+C MM. LEED certification rating levels in this category are as follows: (1) Certified (40-49 points), (2) Silver (50-59 points), (3) Gold (60-79 points), and (4) Platinum (80+ points).

LEED v4 for Building Design and Construction: Multifamily Midrise
Project Checklist

N	Credit	Integrative Process	2
0 0 0		**Location and Transportation**	**15**
N	Prereq	Floodplain Avoidance	Required
		PERFORMANCE PATH	
N	Credit	LEED for Neighborhood Development Location	15
		PRESCRIPTIVE PATH	
N	Credit	Site Selection	8
N	Credit	Compact Development	3
N	Credit	Community Resources	2
N	Credit	Access to Transit	2
0 0 0		**Sustainable Sites**	**7**
N	Prereq	Construction Activity Pollution Prevention	Required
N	Prereq	No Invasive Plants	Required
Y	Credit	Heat Island Reduction	2
Y	Credit	Rainwater Management	3
Y	Credit	Non-Toxic Pest Control	2
0 0 0		**Water Efficiency**	**12**
Y	Prereq	Water Metering	Required
		PERFORMANCE PATH	
N	Credit	Total Water Use	12
		PRESCRIPTIVE PATH	
N	Credit	Indoor Water Use	6
N	Credit	Outdoor Water Use	4
0 0 0		**Energy and Atmosphere**	**37**
Y	Prereq	Minimum Energy Performance	Required
Y	Prereq	Energy Metering	Required
N	Prereq	Education of the Homeowner, Tenant or Building Manager	Required
Y	Credit	Annual Energy Use	30
Y	Credit	Efficieng Hot Water Distribution	5
Y	Credit	Advanced Utility Tracking	2
0 0 0		**Materials and Resources**	**9**
N	Prereq	Certified Tropical Wood	Required
N	Prereq	Durability Management	Required
N	Credit	Durability Management Verification	1
Y	Credit	Environmentally Preferable Products	5
N	Credit	Construction Waste Management	3

0 0 0		**Indoor Environmental Quality**	**18**
N	Prereq	Ventilation	Required
Y	Prereq	Combustion Venting	Required
N	Prereq	Garage Pollutant Protection	Required
N	Prereq	Radon-Resistant Construction	Required
Y	Prereq	Air FIltering	Required
N	Prereq	Environmental Tobacco Smoke	Required
N	Prereq	Compartmentalization	Required
Y	Credit	Enhanced Ventilation	3
N	Credit	Contaminant Control	2
Y	Credit	Balancing of Heating and Cooling Distribution Systems	3
N	Credit	Enhanced Compartmentalization	3
Y	Credit	Enhanced Combustion Venting	2
Y	Credit	Enhanced Garage Pollutant Protection	1
N	Credit	Low Emitting Products	3
N	Credit	No Environmental Tobacco Smoke	1
0 0 0		**Innovation**	**6**
N	Prereq	Preliminary Rating	Required
N	Credit	Innovation	5
N	Credit	LEED AP Homes	1
0 0 0		**Regional Priority**	**4**
Y	Credit	Regional Priority: Specific Credit	1
Y	Credit	Regional Priority: Specific Credit	1
N	Credit	Regional Priority: Specific Credit	1
N	Credit	Regional Priority: Specific Credit	1
0 0 0		**TOTALS** Possible Points:	**110**

Certified: 40 to 49 points
Silver: 50 to 59 points
Gold: 60 to 79 points
Platinum: 80 to 110 points

Figure 4.2 LEED v4 Design and Construction: "Multifamily Midrise" Checklist (adapted from USGBC 2014)

Credits of the LEED v4 Building Design and Construction for Multifamily Midrise rating system are listed in Figure 4.2. The letter "Y" denotes that the credit can be fulfilled completely or partially by one of the four energy analysis tools utilized in this thesis. The letter "N" denotes that the credit is not achievable via BIM-based tools. While the points in the right represent the maximum point that can be obtained for a credit, the word "required" signifies that the credit is a prerequisite.

4.4. Definitions of the Examined LEED Credits

This section describes the main objectives and requirements of all the credits that can be achieved by using four BIM-based tools utilized in this thesis. Explanations of credits for each tool are given in the next section. Points written in the parenthesis denote the maximum points that can be achieved from each credit according to the LEED standards.

4.4.1. Sustainable Sites Category

4.4.1.1. Heat Island Reduction (2 points)

The main objective of this credit is to minimize the effects on microclimates, human life and natural habitats by reducing heat islands. One of the acceptable strategies to get points from this credit is to use non-absorptive materials, such as vegetated roofing. Points are earned by the percentage of hardscape area with shading which does not include the common roads that serve multiple buildings on site (USGBC 2014).

4.4.1.2. Rainwater Management (3 points)

The main objective of this credit is to reduce the amount of rainwater runoff from the building site. One of the acceptable strategies is to increase the permeable area of the building by installing vegetated roofing. As the second case in this credit, percentile rainfall event should be determined to be able to manage on-site water from rainfall events. Points are earned by increasing the permeable area of the building as percentage of total lot area (USGBC 2014).

4.4.1.3. Nontoxic Pest Control (2 points)

The main objective of this credit is to reduce pest problems and minimize the exposure to pesticides. Two items mentioned in the LEED standard are installing ports or openings for all plumbing elements in the slab, and using solid concrete foundation walls, masonry walls or concrete-filled block for below-grade walls. In addition, an integrated pest management policy must be developed for multifamily building projects (USGBC 2014).

4.4.2. Water Efficiency Category

4.4.2.1. Water Metering (Prerequisite)

The main objective of this credit is to promote water efficiency by observing and benchmarking water use for certain time intervals. A water meter or sub-meter should be set for every dwelling unit or the entire building (USGBC 2014).

4.4.3. Energy and Atmosphere Category

4.4.3.1. Minimum Energy Performance (Prerequisite)

The main objective of this credit is to improve energy performance of the building. Proposed building must demonstrate a 5% improvement over the performance of the baseline building. Residential midrise simulation guidelines must be followed to comply with USGBC's requirements. Mandatory provisions of ASHRAE 90.1-2010 standards must be performed. Lastly, commissioning must be performed in order to meet the ENERGY STAR protocols (USGBC 2014).

4.4.3.2. Energy Metering (Prerequisite)

The main objective of this credit is to promote energy efficiency efforts by monitoring and evaluating energy use through time. In order to fulfil this credit, installing an electricity meter or sub-meter for every dwelling unit and a gas meter for whole building, or a gas meter or sub-meter is necessary for each unit (USGBC 2014).

4.4.3.3. Annual Energy Use (30 points)

The main objective of this credit is to improve the overall energy performance of buildings and reduce their GHG emissions. By the applied design-related improvements, it is aimed to demonstrate a percentage improvement in the proposed building's performance compared with the baseline building performance of ASHRAE 90.1-2010. Points are awarded according to the decrease in energy usage that are below the ASHRAE baseline (USGBC 2014).

4.4.3.4. Efficient Hot Water Distribution Systems (5 points)

The main objective of this credit is to reduce the energy consumption and support water supply systems by providing an energy-efficient hot water distribution system. First option requires designing and installing a hot water distribution system based on either certain pipe length requirements or pipe volume limits. Hot water source can be a water heater, boiler, circulation loop piping or heat-traced electric piping. In the second option, on the other hand, installation of at least R-4 insulation on all hot water piping must be performed (USGBC 2014).

4.4.3.5. Advanced Utility Tracking (2 points)

The main objective of this credit is to support the energy efficiency efforts through real-time observations of energy and water use. Only one option of this credit can be achieved via software and is worth 1 point. This option requires installing a permanent energy-monitoring system in each building unit which records at one-hour intervals or less and at the same time, transferring the data regularly to the occupants and the owner (USGBC 2014).

4.4.4. Materials and Resources Category

4.4.4.1. Environmentally Preferable Products (5 points)

The main objective of this credit is to increase the usage of products or building components that reduce material consumption due to having recyclable content, or by materials with overall minimized life-cycle impacts. In this credit, second option can be achieved using BIM-based tools, and this option requires using compliant building components in the construction (USGBC 2014).

4.4.5. Indoor Environmental Quality Category

4.4.5.1. Combustion Venting (Prerequisite)

The main objective of this credit is to minimize leakage of combustion gases into the occupied spaces. A carbon monoxide (CO) monitor is required on each floor of each unit. Moreover, any unvented combustion appliances (ovens and ranges excluded) are not allowed to be installed in the building (USGBC 2014).

4.4.5.2. Air Filtering (Prerequisite)

The main objective of this credit is to protect occupant health by providing an efficient air supply system. On all recirculating space conditioning systems, air filters that have 8 or higher minimum efficiency reporting value (MERV) must be installed per ASHRAE 62.2-2010 standards (USGBC 2014).

4.4.5.3. Enhanced Ventilation (3 points)

The main objective of this credit is to reduce moisture problems and protect occupants from indoor pollutants through advanced ventilation systems. First strategy requires using an automatic humidistat controller, an occupancy sensor, an exhaust fan that operates continuously and a delay timer. As for the second option, installing a whole-house ventilation system that meets the ASHRAE standards is necessary (USGBC 2014).

4.4.5.4. Balancing of Heating and Cooling Distribution Systems (3 points)

The main objective of this credit is to improve thermal comfort and energy efficiency by procuring appropriate space heating and cooling at homes. Among two options that are achievable via software, first option necessitates installing a heating, ventilation and air conditioning (HVAC) system with independent thermostatic controls within at least two zones. A separate loop and separate pump should exist for each zone. As the second option, HVAC system must be designed with thermostatic controls on every radiator (USGBC 2014).

4.4.5.5. Enhanced Combustion Venting (2 points)

The main objective of this credit is to prevent the leakage of combustion gases into the living spaces. First option of this credit requires not installing fireplaces and woodstoves in the building (USGBC 2014).

4.4.5.6. Enhanced Garage Pollutant Protection (1 point)

The main objective of this credit is to protect occupants from pollutants generated from an adjacent garage. If a garage is constructed for the project, it must be a detached garage according to the first option of this credit. As the second option, a garage with more than three cars must be constructed per ASHRAE 62.1-2010 requirements. The exhaust fan in the garage should run continuously or regulated by a carbon monoxide sensor (USGBC 2014).

4.4.6. Regional Priority Category

4.4.6.1. Regional Priority (4 points)

The main objective of this credit is to discuss geographically specific environmental, social and general health priorities. On the USGBC website, there is a database that shows credits which are geographically applicable for any project region. Each Regional Priority credit achieved for a specific location is worth 1 point. Regional priority credit list in USGBC website has six credits including their required point thresholds for the location of the case study building (USGBC 2014).

LEED v4 BD + C: Multifamily Midrise credits are listed in Table 4.1, along with their names and maximum available points that can be achieved in four BIM-based tools used in this thesis.

Table 4.1 LEED v4 BD+C: MM achievable credits using four BIM-based tools

LEED Credit Name	Maximum Points	Autodesk Revit	eQUEST	EnergyPlus	IES-VE
a) Sustainable Sites					
1.Heat island reduction	2	2 - (CSB)	2 - (CSB)	2	2 - (CSB)
2.Rainwater management	3	3 - (CSB)		3	3 - (CSB)
3.Nontoxic pest control	2	1			1
b) Water Efficiency					
1.Water metering	Prerequisite	Required	Required	Required	
c) Energy & Atmosphere					
1.Minimum energy performance	Prerequisite	Required			Required
2.Energy metering	Prerequisite	Required	Required	Required	Required
3.Annual energy use	30	30 - (CSB)		30	30
4.Efficient hot water distribution system	5	5	5	3	3
5.Advanced utility tracking	2	1	1	1	1
d) Material & Resources					
1.Environmentally preferable products	5	5 - (CSB)	5 - (CSB)	5	5 - (CSB)
e) Indoor Environmental Quality					
1.Combustion venting	Prerequisite			Required	
2.Air filtering	Prerequisite		Required		Required
3.Enhanced ventilation	3	3	3	3	3
4.Balancing of heat. and cool. distribution systems	3	3	1	1	1
5.Enhanced combustion venting	2	2 - (CSB)			
6.Enhanced garage pollutant protection	1	1	1		1
f) Regional priority					
1.Regional Priority		2 - (CSB)		2	2 - (CSB)
	Points Achievable ➔	58 Points	18 Points	50 Points	52 Points

While the second left column indicates the maximum points that can be obtained by each credit according to the LEED standards, remaining columns on the right shows the maximum points that can be obtained completely or partially by using the investigated BIM-based tools. For the credits that can be achieved by the case study building, letters "(CSB)" is entered in the table. Finally, the word "required" means that the credit is a prerequisite and it was fulfilled completely or partially by using the investigated BIM-based tools.

4.5. Autodesk Revit

Autodesk Revit is one of the most well-known and used building information modelling tool. It was developed by Charles River Software in 1997, then purchased by Autodesk in 2002 with all rights (Hurley 2019). Revit is mainly used by architects, structural engineers, MEP engineers and designers. Revit allows users to design buildings in 3D and provides functions to track project lifecycle in phases with a coordinated approach. Standardized work-sharing and BIM collaboration connects team members for faster project delivery. Revit simulates and analyses whole building process in Green Building Studio (GBS) to optimize energy efficiency. Numerical analysis supported with graphical demonstrations in GBS allows to create high performance sustainable buildings starting from the design process (Ofluoglu 2016). Another building performance analysis add-in called Insight can be used co-operatively with Revit. Insight contributes to building energy analysis process with key performance indicators, benchmark values, graphical demonstrations and comparisons for different simulation scenarios (Autodesk 2019). While the latest version of Revit is released in 2020, Revit 2018 is used for this thesis study since 2018 version was the most recent edition available at that time.

4.6. Achieving LEED v4 Credits Using Autodesk Revit

Credits that can be achieved using Revit are as follows: **Heat Island Reduction, Rainwater Management, Nontoxic Pest Control, Water Metering, Minimum Energy Performance, Energy Metering, Annual Energy Use, Efficient Hot Water Distribution System, Advanced Utility Tracking, Environmentally Preferable Products, Enhanced Ventilation, Balancing of Heating and Cooling Distribution Systems, Enhanced Combustion Venting, Enhanced Garage Pollutant Protection and Regional Priority.**

4.6.1. Heat Island Reduction

3D model of the vegetated roofing and its properties are shown in Figure 4.3(a) and 4.3(b). Nominal width, absorptance capacity and fill colour may be adjusted as well as the material thickness. Revit also performs solar shading calculations by displaying indirect light and their shadows. Shading simulation of hardscapes is performed using shadow options, sun settings, location, weather and site analysis. The case study building may obtain 2 points partially since further information about the shading of building is unknown.

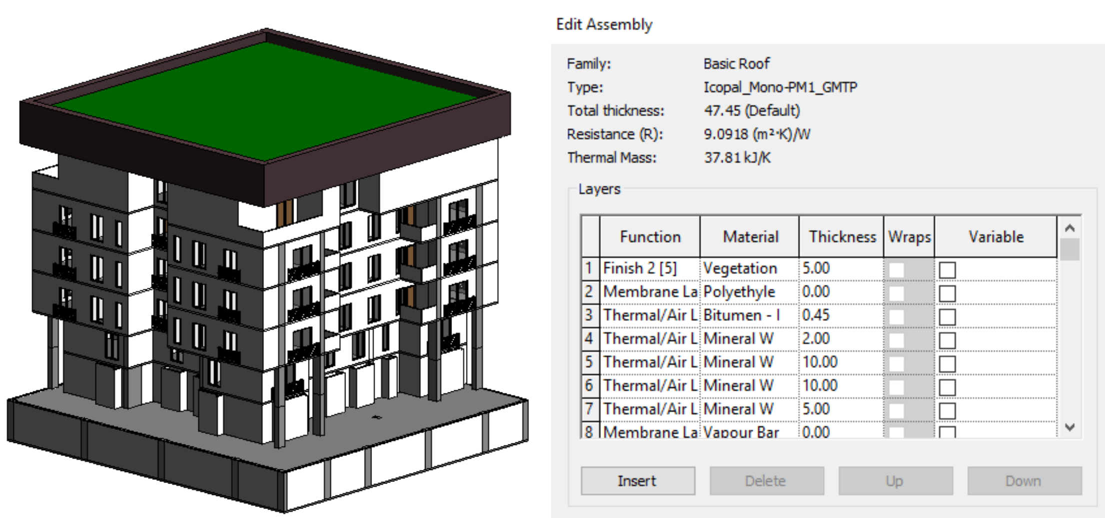


Figure 4.3 (a) Case study building with vegetated roofing, and (b) properties window

4.6.2. Rainwater Management

Installing a vegetated roof in Revit is also an acceptable strategy for this credit. The case study building may obtain 3 points partially since further information about the permeable area of the building is unknown.

4.6.3. Nontoxic Pest Control

Each item in this credit is worth 0.5 points and two of them can be achieved in Revit. These items require installing ports or openings for all plumbing elements in the slab and using solid concrete foundation walls, masonry walls or concrete-filled block for below-grade walls. Therefore, 1 point can be obtained completely by using Revit.

4.6.4. Water Metering

As the result of the energy analysis in Revit, water usage and cost calculations are conducted in terms of indoor and outdoor water use and total use. Unit water prices for water and sewer, number of people and percent of time occupied are considered for the net utility. Thus, this prerequisite can be fulfilled completely by using Revit. Figure 4.4 shows the usage rate calculations demonstrated in GBS interface.

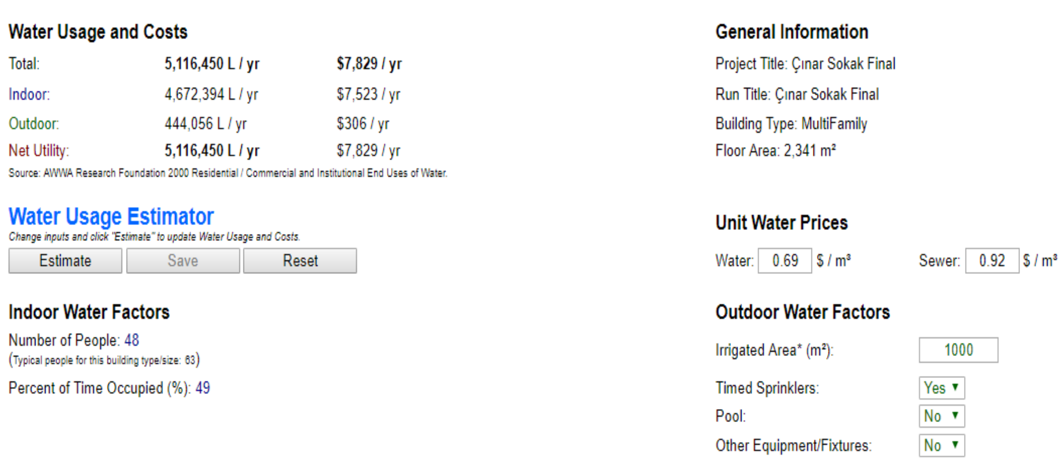


Figure 4.4 Water usage and related costs displayed in GBS

4.6.5. Minimum Energy Performance

Baseline building performance based on ASHRAE 90.1-2010 Standard is calculated in GBS. In Insight's benchmark comparison and graphical demonstration techniques allow to demonstrate percentage improvement over ASHRAE baseline. Figure 4.5 shows the benchmark comparison of annual energy consumption rates for the proposed building. In the figure, yearly energy consumption performance of the proposed building is compared with ASHRAE baseline performance values. This prerequisite may be fulfilled partially by the case study building since commissioning cannot be performed by Revit.

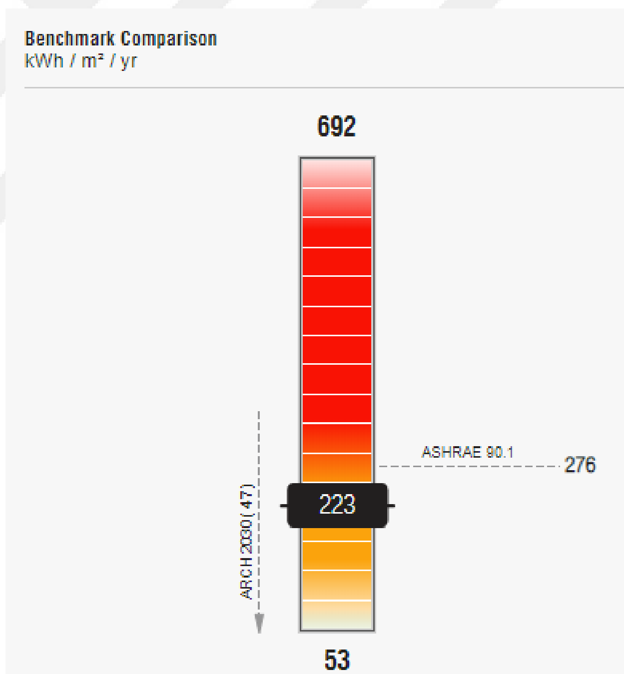


Figure 4.5 Energy consumption of proposed building and ASHRAE baseline in Insight

4.6.6. Energy Metering

As the main purpose of the energy analysis in Revit, energy calculations are performed, and the results are indicated in many ways. Total annual energy usage and cost are demonstrated in GBS in terms of electric and fuel. Thus, this prerequisite can be fulfilled completely by using Revit. In Figure 4.6 below, various energy analysis and cost figures are shown in GBS.

Display Options

Energy Use Intensity (MJ/m²/year)	Electric Cost (/kWh)	Fuel Cost (/MJ)	Total Annual Cost [1]			Total Annual Energy [1]			Compare	Beta Potential Energy Savings
			Electric	Fuel	Energy	Electric (kWh)	Fuel (MJ)	Carbon Emissions (Mg)		
Weather Data: GBS_06M12_02_274069										
--	$0.14	$0.01	--	--	--	--	--	--		
1,033.0	$0.14	$0.01	$32,191	$21,681	$53,872	231,589	1,584,501	--		

Figure 4.6 Total annual energy and related costs displayed in GBS

4.6.7. Annual Energy Use

By means of the alternate runs simulated in GBS, energy analysis results of baseline building performance for ASHRAE 90.1-2010 can be discovered. Base run and alternate run created in GBS are shown in Figure 4.7 below. Comparison of the proposed building and ASHRAE baseline can be performed, and thus, the case study building can obtain 30 points completely.

Name	Date	User Name
Project Default Utility Rates		
Project Default Utility Rates	--	--
Base Run		
Çınar Sokak Final	3/31/2019 2:51 PM	berkantbayar
Alternate Run(s) of Çınar Sokak Final		
Çınar Sokak Final_ASHRAE 90.1-2010	3/31/2019 2:56 PM	berkantbayar

Figure 4.7 Proposed building performance vs baseline building performance in GBS

4.6.8. Efficient Hot Water Distribution System

A hot water distribution system can be installed in Revit with a water heater, boiler and a circulation loop piping as the source of hot water. Pipe length, flow rate and insulation type can be edited. Circulation pipe operations are controlled by occupancy schedules, power schedules and opening/closing time options. Thus, 5 point may be obtained partially by using Revit since some other requirements, such as temperature sensor regulations, water temperature, pump limits, testing procedures etc. cannot be achieved via the software.

4.6.9. Advanced Utility Tracking

Considering one of the main characteristics of Revit; 8,760 hours of building operation is calculated in order to simulate the annual energy use. For this reason, 1 point can be obtained completely by using Revit.

4.6.10. Environmentally Preferable Products

For this credit, 5 points can be obtained completely by the case study building, since all the building components listed in table 4.2 below can be modelled using Revit. These materials can be modelled either using default shapes or adding material from the library.

Table 4.2 Points received by using compliant building components (adapted from USGBC 2014)

Component	Maximum Points
Flooring - Base floor only (i.e., sealed concrete, no floor covering)	2
Floor covering	1
Insulation	1
Sheathing	1
Framing	1
Drywall, interior finish	1
Concrete: cement and / or aggregate	1
Roofing	1
Siding	1
Additional components (install at least 3 of the following):	
Doors (not including insulated doors or garage door)	1
Cabinets	
Counters (kitchens and bedrooms)	
Interior trim	
Decking or patio material	
Windows	

4.6.11.Enhanced Ventilation

An enhanced ventilation system can be installed in Revit with all the necessary HVAC building components. A continuously operating exhaust fan can also be used in building/space type settings tab. Therefore, 3 points may be obtained partially from this credit since minimum ventilation requirements of ASHRAE standards can't be met by using Revit.

4.6.12. Balancing of Heating and Cooling Distribution Systems

With independent thermostatic controls on two zones, an HVAC system can be installed. In addition, Revit allows to design an HVAC system with flow-control valves on every radiator. Therefore, 3 points can be obtained completely from this credit.

4.6.13. Enhanced Combustion Venting

In Revit, a fireplace and a woodstove can be modelled by loading families of combustion venting devices from the family library. Therefore, the case study building can obtain 2 points completely from this credit.

4.6.14. Enhanced Garage Pollutant Protection

A garage that does not share a wall with the building can be modelled in Revit by using multiple techniques such as constructing structural walls, concrete slab and adding various door materials. Accordingly, 1 point can be obtained completely from this credit.

4.6.15. Regional Priority

In the regional priority credit list in USGBC website, there are two credits that can be achieved by using Revit. Required point thresholds of 15 points and 2 points accordingly for credits “Annual Energy Use” and “Rainwater Management” may be exceeded. Thus, 2 points can be obtained completely by the case study building from this credit.

Based on the exploration of the Revit features, it was concluded that 15 LEED credits including 3 prerequisites that worth a total of 58 points may be completely or partially performed using Revit. Due to some of the other requirements which cannot be achieved via the software, some credits are classified to be partially performed. These other requirements may involve preparation of LEED documents, installing devices by following some standards or further information about the project. Among these 15 credits, 9 of them are being achieved by the case study building, while 6 of them can be achieved independently by Revit’s features.

4.7. eQUEST

eQUEST is a freeware building energy use analysis tool that allows to perform detailed building energy designs. eQUEST interoperates with the simulation engine DOE-2 that was developed by James J. Hirsch & Associates in collaboration with Lawrence Berkeley National Laboratory (LBNL) (DOE-2 2019). It guides the users through the creation of a detailed DOE-2 building model to perform parametric simulations of different design alternatives. Without extensive experience in building performance modelling, comparative analysis of sophisticated simulation techniques can be implemented. Most recent release of eQUEST is the version 3.65 developed in 2018 and it was used for this thesis.

4.8. Achieving LEED v4 Credits Using eQUEST

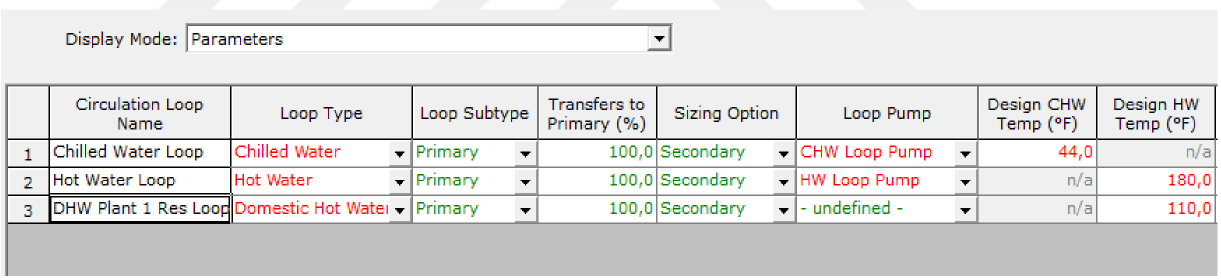
For the investigation of the LEED v4 credits, the case study building was first modeled in Revit 2018, and then the 3D model was exported to eQUEST v3.65. Credits that can be achieved using eQUEST are as follows: **Heat Island Reduction, Water Metering, Energy Metering, Efficient Hot Water Distribution System, Advanced Utility Tracking, Environmentally Preferable Products, Air Filtering, Enhanced Ventilation, Balancing of Heating and Cooling Distribution Systems and Enhanced Garage Pollutant Protection.**

4.8.1. Heat Island Reduction

In eQUEST, two types of shading can be modelled: Trees that are separate from the building are detached shades and overhangs that are connected to building are attached shades. Details of building shades in a project are listed with the information of solar transmittance in winter and summer time for a tree. It also calculates hourly shading factors using hourly sun positions for each month. The case study building may obtain 2 points partially since further information about the hardscape area of building is unknown.

4.8.2. Water Metering

In the Water-Side HVAC module of eQUEST, three main water-related HVAC system components such as chiller, boiler and water heater are modelled according to the user selection. Chiller properties can be adjusted in terms of equipment capacity (units in MBtu/h), water temperature, condenser characteristics and other design conditions. Boiler and water heater properties include minimum and maximum flow ratios, start-up and standby times, loop assignments and other specifications. Metering of these HVAC components can be performed with operational and utility costs. Figure 4.8 displays the spreadsheet of Water-Side HVAC equipment with different parameters. Thus, this prerequisite may be fulfilled partially by using eQUEST due to lack of billing information.



Display Mode: Parameters

	Circulation Loop Name	Loop Type	Loop Subtype	Transfers to Primary (%)	Sizing Option	Loop Pump	Design CHW Temp (°F)	Design HW Temp (°F)
1	Chilled Water Loop	Chilled Water	Primary	100,0	Secondary	CHW Loop Pump	44,0	n/a
2	Hot Water Loop	Hot Water	Primary	100,0	Secondary	HW Loop Pump	n/a	180,0
3	DHW Plant 1 Res Loop	Domestic Hot Water	Primary	100,0	Secondary	- undefined -	n/a	110,0

Figure 4.8 Water-Side HVAC spreadsheet in eQUEST

4.8.3. Energy Metering

DOE-2 introduced the concept of meters for electricity and fuel end uses in order to report the energy consumption. Additionally, a utility rate schedule associated with the meter allows disaggregating energy use and cost. Annual and monthly utility meter reports produced for all electric and fuel uses. Annual run reports and electric meters by end use are prepared in terms of area lighting, electric equipment, space heating, space cooling, pumps and miscellaneous, ventilation fans, refrigeration, supplemental heat and domestic hot water.

Annual run reports and end uses in terms of fuel meters include source fuel, space heating, space cooling, supplemental heat and domestic hot water. Thus, this prerequisite may be fulfilled completely by using eQUEST. In Figure 4.9 below, an example of end use rates in terms of electric and gas consumption are shown in eQUEST results view.

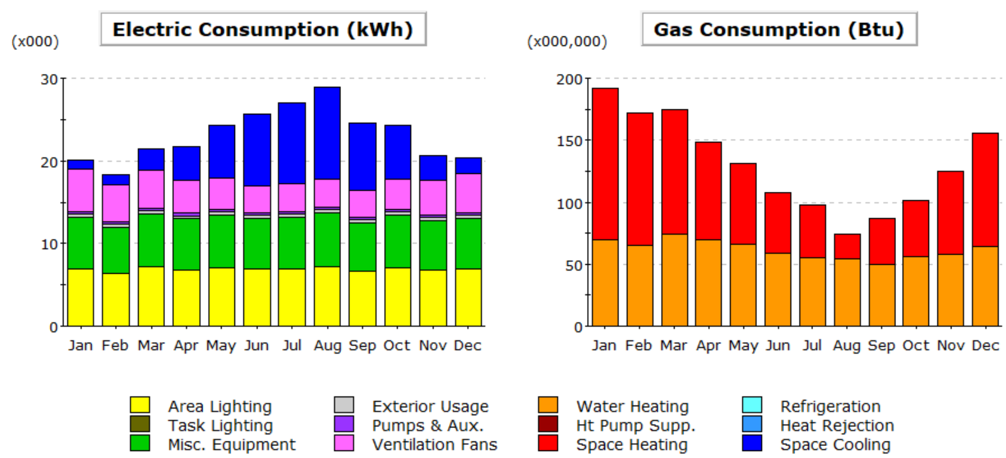


Figure 4.9 Graphical representation of consumption rates in eQUEST

4.8.4. Efficient Hot Water Distribution System

In eQUEST's Schematic Design Wizard, up to two boilers can be modelled. Hot water circulation loops are also designed in terms of loop volume (units in gallon). Hot water use, storage tank capacity and insulation R-values can be adjusted in water heater specifications window shown in figure 4.10 below. HVAC system schedules can also be adjusted hourly for all weekdays and holidays. Accordingly, 5 points may be obtained partially since some other requirements cannot be achieved via the software (USGBC 2014).

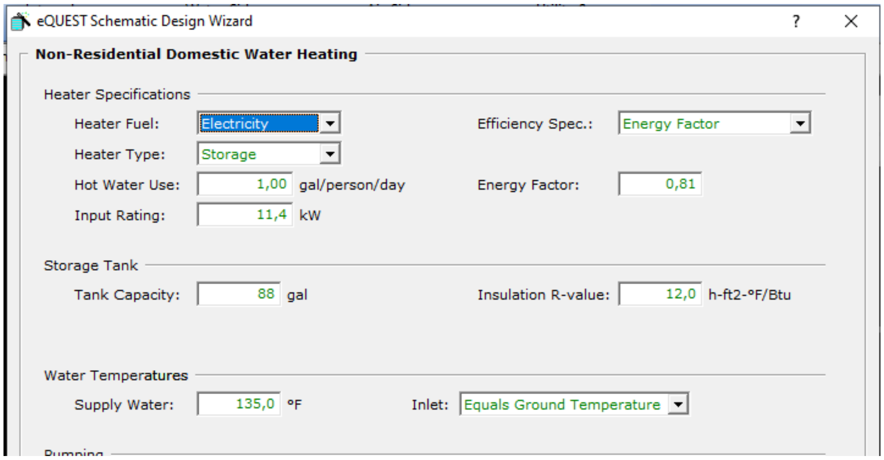


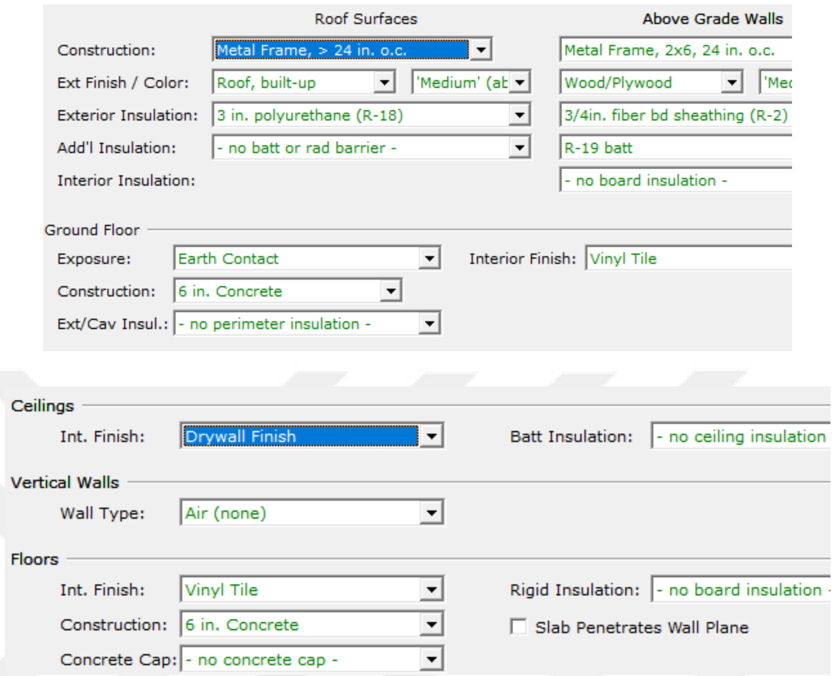
Figure 4.10 Domestic water heating specifications in eQUEST

4.8.5. Advanced Utility Tracking

Over an entire year (i.e., 8,760 hours), eQUEST calculates hour-by-hour building energy consumption using weather data for a specific location. In eQUEST's detailed interface, schedules can be edited hourly and many operational seasons can be used in spreadsheets. In addition, demand interval is in between 5 to 60 minutes with 5-minute increments to calculate end-use categories for relatively short durations. In this credit, 1 point can be obtained completely by using eQUEST.

4.8.6. Environmentally Preferable Products

The case study building can obtain 5 points completely from this credit, since most of the building components listed below is available in eQUEST. Unlike Revit, building components to be modelled are selected before the creation of the 3D model. eQUEST's Schematic Design Wizard allows to choose the preferred materials for different purposes. In the list of USGBC's compliant building components, flooring, floor covering, insulation, sheathing, drywall, interior finish, concrete, roofing, siding, doors and windows are available. Figures 4.11 and 4.12 show the building envelope constructions, interior constructions and other components selection window.



Figures 4.11-4.12: Building material options in eQUEST

4.8.7. Air Filtering

In Air-Side systems, MERV 9 to 15 air filters can be installed for fully ducted returns and heat recovery devices per ASHRAE standards. Thus, this prerequisite can be fulfilled completely by using eQUEST.

4.8.8. Enhanced Ventilation

A whole-house ventilation system can be installed in eQUEST within Air-Side HVAC module. Air-Side HVAC system parameters window helps users to model features of outdoor ventilation air, natural ventilation methods, outside air control and night venting schedules. At the same time, humidity control can be done by the specifications of maximum/minimum humidity, humidifier type and location. 3 points may be obtained partially by using eQUEST due to lack of information about requirements of ASHRAE Standard 62.2-2010. Some examples of HVAC system parameters are displayed in figure 4.13.

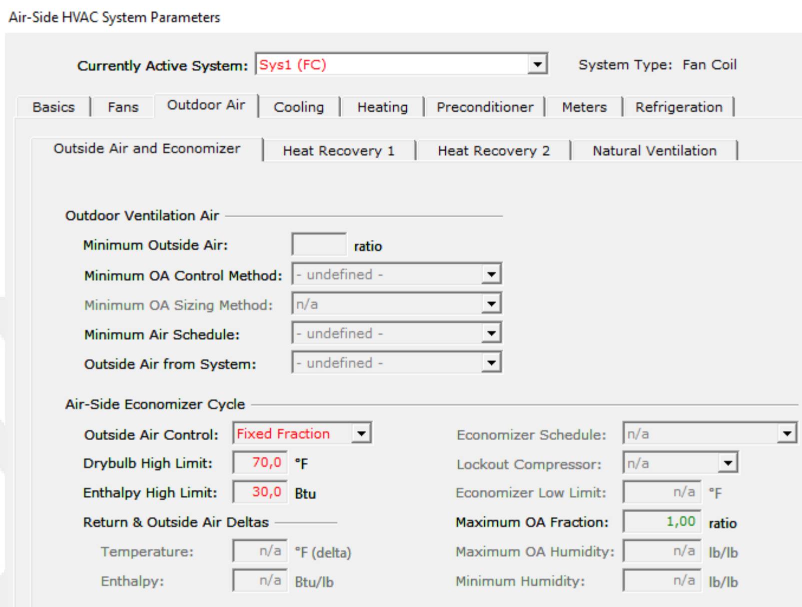
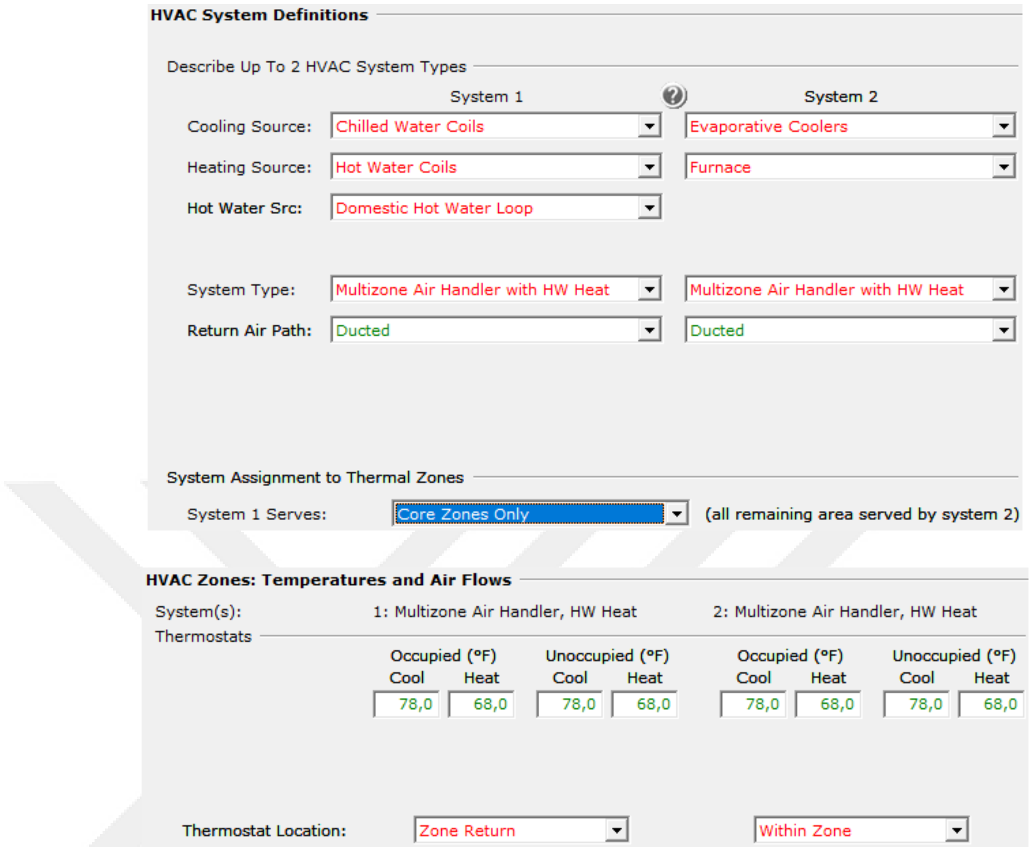


Figure 4.13: Air-Side HVAC system parameters in eQUEST

4.8.9. Balancing of Heating and Cooling Distribution Systems

One of the features of eQUEST is HVAC zoning and generally one exterior zone, one internal zone and one plenum zone is generated for special uses. Thermostat settings and schedules are recorded per HVAC zone in operations spreadsheet. Each zone has a separate loop and separate pump controlled by an independent thermostat. Figures 4.14 and 4.15 show different HVAC system types, assignments to thermal zones and thermostatic controls in HVAC system definitions screen. By using eQUEST, 1 point can be obtained completely from this credit.



Figures 4.14-4.15: HVAC system definitions in eQUEST.

4.8.10. Enhanced Garage Pollutant Protection

In the second option of this credit, installing an exhaust fan that runs continuously in a garage is required. eQUEST is not capable of modelling a detached garage, however an attached garage can be modelled with an exhaust fan in it. An exhaust fan is scheduled to run continuously in Air-Side HVAC system parameters section. 1 point may be obtained partially from this credit by using eQUEST due to limited information of ASHRAE Standard 62.2-2010 standards and other tasks that cannot be done via the software.

As the result of the exploration of eQUEST features, it was concluded that 10 LEED credits including 3 prerequisites that is worth a total of 18 points may be completely or partially performed. Due to some other requirements which cannot be achieved via the software, some credits are classified as partially performed. Other requirements may involve further information of ASHRAE standards and details of some building components. Among these 10 credits, 2 of them were achieved by the case study building, while 8 of them were achieved independently by eQUEST's features.

4.9. EnergyPlus

Whole building energy simulation program of EnergyPlus is under development since 1997 to assist engineers, architects and designers modelling energy consumption. This open-source building energy modelling (BEM) engine has many simulation characteristics inherited from DOE-2 that is being the successor to DOE-2.1E (EnergyPlus 2019). Main features of EnergyPlus include calculating energy consumption of plant equipment, performing thermal simulation at sub-hourly time steps and providing environmental performance data (EnergyPlus 2019). It reads input and writes output based on a user's description of a building. While the latest version of EnergyPlus is 9.2 updated in 2019, previous version (v8.9) is used for this thesis since that version was the most recent edition available at the time.

4.10. Achieving LEED v4 Credits Using EnergyPlus

As mentioned before, for the investigation of the LEED v4 credits, the case study building was first modeled in Revit 2018. Thereafter, 3D model was exported to EnergyPlus from Revit 2018 as the third tool examined in the thesis study. EnergyPlus does not provide 3D visualization of the model exported from Revit, however, can still perform calculations over the imported Revit models. Credits that can be achieved using EnergyPlus are as follows: **Heat Island Reduction, Rainwater Management, Water Metering, Energy Metering, Annual Energy Use, Efficient Hot Water Distribution System, Advanced Utility Tracking, Environmentally Preferable Products, Combustion Venting, Enhanced Ventilation, Balancing of Heating and Cooling Distribution Systems and Regional Priority.**

4.10.1. Heat Island Reduction

Green roofs (i.e., vegetated roof) can be modelled as a non-absorptive material in EnergyPlus. For the other option of this credit, shading calculations are done for periods of time by locating trees as detached shading surface and calculating interior and exterior sunlit areas using shading module. Gross and net area of building surfaces are shown for the purposes of shading calculations. 2 points may be obtained partially in this credit due to lack of information about the hardscape area of the proposed building.

4.10.2. Rainwater Management

As an acceptable strategy for this credit, EnergyPlus allows user to model green roofs also known as eco roofs or vegetated roofs. Various aspects of the green roof construction such as growing media depth, thermal properties, plant height and soil moisture conditions can also be specified. Therefore, 3 points may be obtained partially since further information about permeable area of a proposed building is missing.

4.10.3. Water Metering

In EnergyPlus, different resource types including water are metered in cubic meters (m^3). Annual building utility performance summary report, end use values, water source summary report with annual, maximum and minimum values, utility use per conditioned floor area and total floor area reports are metering water used in the building. Tariff conversion factors for water meters allow to determine utility costs. Thus, this prerequisite can be fulfilled completely by using EnergyPlus.

4.10.4. Energy Metering

Resource types of electricity, gas and fuel are metered along with sub-meters of zone, building, system and plant components. Annual energy and demand values are shown in units of Joules (J) and Joules/Sec (J/s). Annual building utility performance summary report provides an overview of building energy consumption for different end uses. Tariff conversion factors for electric and gas meters allow to determine utility costs. Total energy costs per total building area and net conditioned building area are calculated annually in terms of electricity and natural gas. Thus, this prerequisite can be fulfilled completely by using EnergyPlus. Figure 4.16 below shows the table of metered resource types.

Utility/Fuel Types	
Electricity	Gas
Gasoline	Diesel
Coal	FuelOil#1
FuelOil#2	Propane
Water	Steam
DistrictCooling	DistrictHeating

Figure 4.16 Metered resource types in EnergyPlus (EnergyPlus 2019)

4.10.5.Annual Energy Use

Baseline building performance according to the standards of ASHRAE 90.1-2010 can be generated by simulating the building with four different (i.e., actual, 90^{o}, 180^{o}, 270^{o})

orientations. Comparison of proposed design versus baseline design is performed using "Model Input Parameters" (Energy Plus 2019). Therefore, 30 points can be obtained completely from this credit by using EnergyPlus.

4.10.6. Efficient Hot Water Distribution System

A water heater or boiler can be modelled in EnergyPlus as the hot water source. Pipe length is defined in meters between the farthest terminal unit and the heat pump condenser. Pipe volume is also computed with maximum loop volumetric flow and design flow rate (units in cubic meter / second) values. An operating schedule is available with on/off switch options for hot water distribution. In figure 4.17 below, a simple line diagram for a heating loop is illustrated. 3 points can be obtained completely by using EnergyPlus.

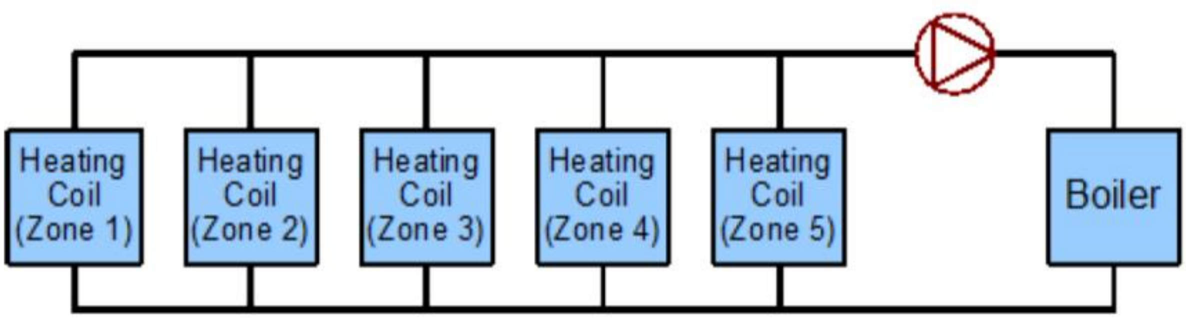


Figure 4.17 Line diagram of a heating loop in EnergyPlus (Energy Plus 2019)

4.10.7. Advanced Utility Tracking

EnergyPlus can simulate a building at time steps of less than one hour. This sub-hourly simulation program does energy performance analysis and load calculations for 1 hour to even 15 minutes. Therefore, by using EnergyPlus, 1 point can be obtained completely from this credit.

4.10.8. Environmentally Preferable Products

Building components that can be modelled in EnergyPlus are flooring, roofing, floor covering, insulation, doors and windows. In addition, number of kitchens and bathrooms that take place in the model is determined by the user as an input. 5 points can be obtained completely from this credit by modelling these building components.

4.10.9. Combustion Venting

Thirteen different pollutants including carbon monoxide are calculated in terms of mass and volume based on emission factors in EnergyPlus. Thus, this prerequisite may be fulfilled partially using EnergyPlus since there are other requirements that cannot be done via the software.

4.10.10. Enhanced Ventilation

Using EnergyPlus, a whole-house ventilation system can be installed with control parameters of minimum temperature, wind speed, zone floor area, number of occupants, fan efficiency and other related specifications. Different types of ventilation such as mechanical, simple, natural, zone, night and hybrid ventilation can be simulated. One humidistat controller is also available for each zone. From this credit, 3 points may be obtained partially by using EnergyPlus due to lack of information about requirements of ASHRAE Standards.

4.10.11. Balancing of Heating and Cooling Distribution Systems

Thermostatic controls are installed in systems with at least two space-conditioning to meet any heating requirement in EnergyPlus. In ZoneHVAC:AirDistributionUnit option, all equipment that control the air going into each individual zone with respect to the preferred thermostatic control are regulated. Accordingly, 1 point can be obtained completely in

EnergyPlus. Thermostatic controls in terms of different zones are illustrated in figure 4.18 below.

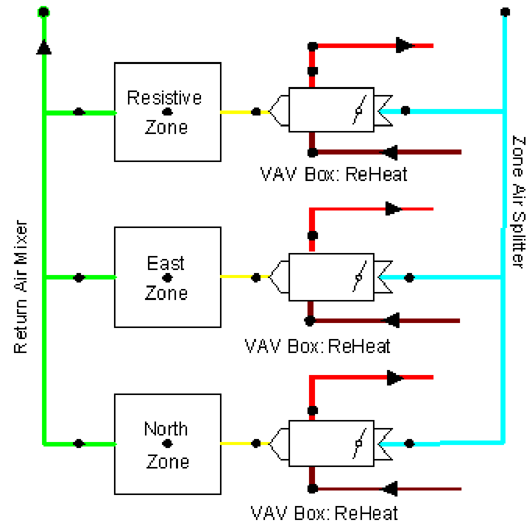


Figure 4.18 Zone thermostatic control in EnergyPlus (Energy Plus 2019)

4.10.12. Regional Priority

In the regional priority credit list in USGBC website, there are two credits that can be achieved by using EnergyPlus. Required point thresholds of 15 points and 2 points accordingly for "Annual Energy Use" and "Rainwater Management" can be exceeded. Thus, 2 points can be obtained completely by using EnergyPlus.

Based on the examinations on EnergyPlus features, it was concluded that 12 LEED credits including 3 prerequisites that is worth a total of 50 points may be completely or partially achieved. Due to some other requirements which cannot be performed via the software, some credits are classified as partially performed. Other requirements may involve further information of ASHRAE standards and missing details of some building components. In this section, case study building model did not display in 3D in EnergyPlus interface since this BIM-based tool has a limited 3D interface available to be modified by a user. EnergyPlus requires integration of other simulation tools (i.e., SketchUp or OpenStudio) for 3D presentation, however, those simulation tools were left out of the scope in this study.

4.11. IES-VE

IES Virtual Environment (VE) was founded by Don Mclean from University of Strathcylde in 1994 (IESVE 2019). IES-VE is a building performance simulation tool that can be used by designers to compare different solutions, identify renewable technologies and make analysis on energy use, occupant comfort and CO2 emissions. This tool has three fundamental objectives: making buildings more energy efficient to reduce CO2 emission, minimizing fossil fuels, and preserving the environment for future generations (Buckley 2013). Resource-efficient and cost-effective built environments can be simulated by making sustainable decisions. Latest version of IES-VE for engineers is 2019, however, previous version (2018) is used since 2019 version was not fully released during the study.

4.12. Achieving LEED v4 Credits Using IES-VE

For the investigation of LEED v4 credits, the case study building was first modeled in Revit 2018, and then the 3D model was exported from Revit to IES-VE 2018 as the last tool that was examined in the thesis study. Credits that can be achieved using IES-VE are as follows: **Heat Island Reduction, Rainwater Management, Nontoxic Pest Control, Minimum Energy Performance, Energy Metering, Annual Energy Use, Efficient Hot Water Distribution System, Advanced Utility Tracking, Environmentally Preferable Products, Air Filtering, Enhanced Ventilation, Balancing of Heating and Cooling Distribution Systems, Enhanced Garage Pollutant Protection and Regional Priority.**

4.12.1. Heat Island Reduction

Shading calculations are undertaken in the modules of RadienceIES and SunCast in IES-VE (IES-VE 2018). While SunCast defines shading surfaces, computes the geometric position of the sun and the building at any time and reports the percentage of sunlight on internal and external surfaces, RadienceIES defines shading surfaces and daylight information in order to perform lighting simulations. Moreover, a roof can be installed as a green roof in project constructions option. Therefore, 2 points may be obtained partially by the case study building using IES-VE since limited information is known about the hardscape area of the case study building. Figure 4.19 demonstrates the case study building with the green roof and green coloured local shading in model viewer.

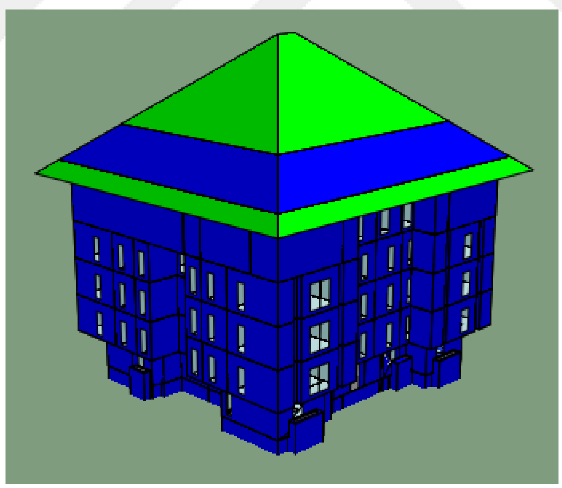


Figure 4.19 Case study building displayed in IES-VE interface

4.12.2. Rainwater Management

As explained in the previous credit, a green roof can be installed and that can increase the permeable area of the case study building. As the second case of this credit, assessments of water storage solutions are performed about the site rainfall runoff and 95th / 98th percentile rainfall event calculations allow to obtain points for on-site management of water (IES-VE 2018). Thus, 3 points may be obtained partially by using IES-VE since further information about permeable area of the case study building is needed.

4.12.3. Nontoxic Pest Control

First of two items in this credit requires installing ports or openings for the plumbing material in the building. In MacroFlo module of IES-VE, several openings regarding windows, door and duct systems can be managed. Solid concrete foundation walls, masonry walls or concrete-filled blocks are also modelled for below-grade walls. Accordingly, 1 point can be obtained completely from this credit using IES-VE. Modules defined in the limited version of IES-VE 2018 can be seen in Figure 4.20 below.

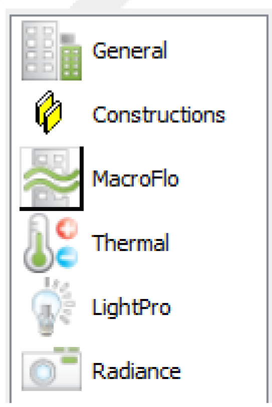


Figure 4.20 Modules of IES-VE 2018 in the building template manager tab

4.12.4. Minimum Energy Performance

In order to comply with multifamily midrise simulation guidelines of USGBC, IES-VE provides compliance for ASHRAE 90.1 Appendix G standards. VE-NAVIGATOR module (IES-VE 2018) covers the standards of performance rating method and energy cost budget for LEED analysis. In addition, module of IES-ERGON undertakes commissioning required by LEED v4. Thus, this prerequisite can be fulfilled completely by using IES-VE.

4.12.5. Energy Metering

Different kinds of energy sources are metered with CO_2 emissions factors in energy sources and meters tab. In addition, sub-metering options are collecting information in VistaPro module of IES-VE. 25 energy sources that can be customized are also offered as well as the predefined types. Operational costs and fuel tariffs in terms of electricity and natural gas are also calculated as the result of the advanced dynamic thermal simulation in the central simulation processor of APACHESIM (IES-VE 2018). This prerequisite can be fulfilled completely by using IES-VE. Figure 4.21 shows the table of metered energy sources.

No	Name	CO2 Emission Factor	Meters
0	Natural Gas	0.21600	Meter 1,
1	LPG	0.24100	Meter 1,
2	Biogas	0.09800	Meter 1,
3	Oil	0.31900	Meter 1,
4	Coal	0.34500	Meter 1,
5	Biomass	0.03100	Meter 1,
6	Electricity	0.51900	Meter 1,
7	Waste Heat	0.05800	Meter 1,
8	Anthracite	0.39400	Meter 1,
9	Smokeless Fuel (inc Coke)	0.43300	Meter 1,
10	Dual Fuel Appliances (Mine...	0.22600	Meter 1,

Figure 4.21 Energy sources and meters in IES-VE

4.12.6. Annual Energy Use

Using Parallel Simulation Manager which is a module of IES-VE that allows to run multiple simulations simultaneously, baseline building according to ASHRAE 90.1-2010 standards can be automatically generated. Through creating separate models in dynamic simulations, comparison of proposed and baseline design is made to carry out a percentage improvement. Subtotals of energy use and cost along with percent savings for proposed and baseline design are demonstrated in Figure 4.22 below. By using IES-VE, 30 points can be obtained completely.

Energy Type	Units	Proposed Design		Baseline Design		Percent Savings	
		Energy Use	Cost (USD)	Energy Use	Cost (USD)	Energy Use	Cost
Electricity	kBtu	201,680.67	8,511.38	279,599.39	11,799.72	27.87	27.87
Gas	kBtu	144,867.09	0.00	237,877.41	0.00	39.10	0.00
Subtotal (Model Outputs):		346,547.77	8,511.38	517,476.80	11,799.72	33.03	27.87

Figure 4.22 Proposed design vs baseline design in IES-VE

4.12.7. Efficient Hot Water Distribution System

As the source of hot water in a hot water distribution system, water heater, boiler and electric heat-traced piping can be modelled in IES-VE. Circulation loop length is determined in meters as the pipe length in hot water distribution system. To reduce energy consumption, an automated optimal start option is used for the start-up time determination. Since some requirements of this credit cannot be fulfilled using software, 3 points may be obtained partially.

4.12.8. Advanced Utility Tracking

Over an annual period, it is possible to have simulation data of 8,760 hours. While the energy analysis can be performed annually and monthly, hourly and sub-hourly time steps are also available upon request. Thus, 1 point can be obtained completely by using IES-VE from this credit.

4.12.9. Environmentally Preferable Products

In the list of USGBC's compliant building components list, flooring as ground floor, floor covering, insulation, roofing, doors, internal and external windows and concrete patio as hard landscape are modelled in IES-VE. From this credit, 5 points can be obtained completely by the case study building using IES-VE.

4.12.10. Air Filtering

MERV-13 filtration can be installed on space conditioning systems. Baseline fan-power adjustment is calculated per ASHRAE standards. This prerequisite can be fulfilled completely by using IES-VE.

4.12.11. Enhanced Ventilation

In the building template manager tab of IES-VE, humidity control is applied with maximum and minimum saturation percentages. In addition, optimum start/stop control and operation profile options can work as a delay timer to operate the fan for different time intervals. A whole-house ventilation system can also be set using outdoor air ventilation, auxiliary ventilation system and seasonal heat recovery options. 3 points can be obtained partially from this credit since the requirements of ASHRAE standards cannot be met by using IES-VE.

4.12.12. Balancing of Heating and Cooling Distribution Systems

In buildings that have both a heating and cooling system, at least two space-conditioning zones can be simulated. Each HVAC zone may have its own thermostat control for both heating and cooling spaces. Thus, 1 point can be obtained completely by using IES-VE from this credit.

4.12.13. Enhanced Garage Pollutant Protection

In order to follow the requirements of LEED, ASHRAE 62.1 is provided in IES-VE. An exhaust fan that run continuously can be adjusted as on/off continuously by variation profile selection. Basis for ventilation and exhaust options are shown in Figure 4.23. Therefore, 1 point may be obtained partially from this credit by using IES-VE since some other tasks cannot be performed via the software.

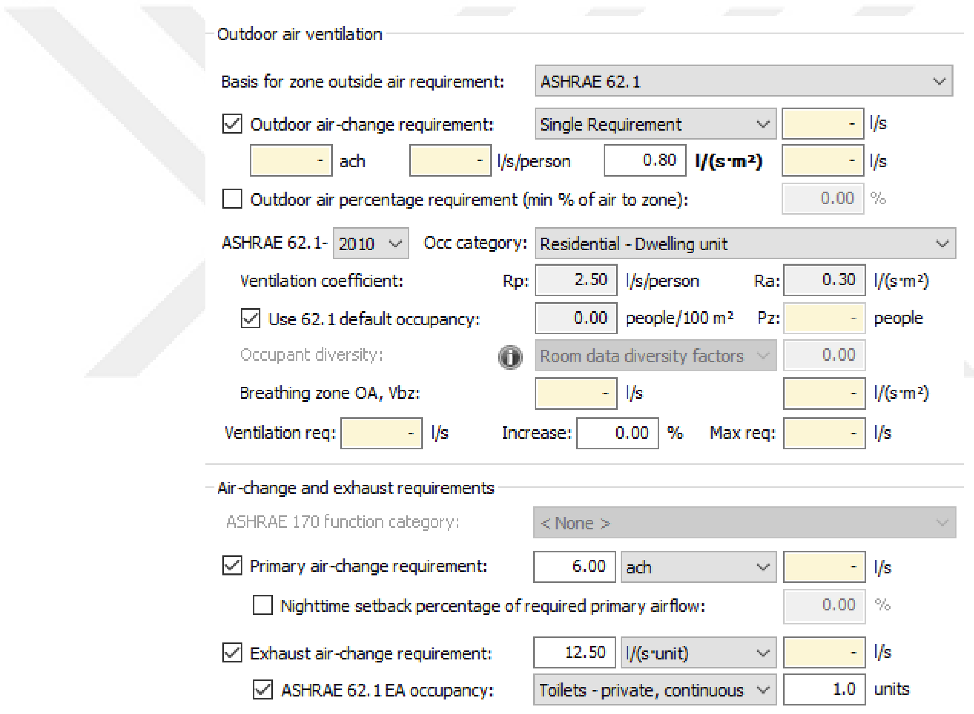


Figure 4.23 Ventilation requirements and exhaust options in HVAC system

4.12.14. Regional Priority

There are two credits that can be achieved by using IES-VE in USGBC’s regional priority credit list. Required point thresholds of 15 points and 2 points accordingly for “Annual Energy Use” and “Rainwater Management” may be exceeded. Thus, 2 points can be obtained by the case study building completely using IES-VE.

As the result of the investigations on IES-VE features, it was concluded that 14 LEED credits including 3 prerequisites that is worth a total of 52 points may be completely or partially performed. Due to some other requirements which cannot be performed by using the software, some credits are classified as partially performed. These requirements involve limited knowledge about the ASHRAE standards and some unknown details of important building components. Among 13 credits that can be fulfilled by using IES-VE, 4 of them are achieved by the case study building.

CHAPTER V

RESULTS

5.1. Limits of Software Support for LEED Categories

Energy analysis tools, thanks to the advancements in the field of computer-aided energy analysis, can help create designs that fulfil LEED credits. Software support during the early stages of construction allows to design green buildings and qualify these buildings for certification by following the standards at the same time. However, support of software in this process might be limited since some credits have requirements that cannot be performed via the use of a certain software. Since completely achieving a credit depends on the availability of data related to the project; a credit can only be achieved partially by using a BIM-based tool if there is missing data about the project. For instance, according to the credit in the "Integrative Process" category and the first credit in the "Innovation" category called "Preliminary Rating", training sessions on green aspects of the project, workshops or other meetings that necessitate involvement of project team are required (USGBC 2014) so that the project can include some innovative details. In that sense, a software cannot be helpful to achieve these credits. However, BIM-based tools have the potential to provide a platform to review design alternatives in an innovative and cost-effective point of view. Advantages of BIM-based tools related to "Integrative Process" and "Innovation" category are not in the scope of this thesis.

5.2. LEED Categories Achievable by Software Support

At least one credit is applicable for software support in the remaining six LEED categories (i.e., Sustainable Sites, Water Efficiency, Energy and Atmosphere, Material and Resources, Indoor Environmental Quality and Regional Priority). In “Energy and Atmosphere” category, almost every credit can be achieved using BIM-based tools. Main idea here is metering of the whole building in terms of several energy sources and providing minimum requirements for building performance. Additionally, a baseline building that is designed according to ASHRAE standards must be modelled in order to be compared with the proposed building that is in pursuit of LEED certification. Approximately half of the “Sustainable Sites” and “Indoor Environmental Quality” credits could be performed via the assistance of a software. As the former includes shading calculations and using green roofing materials, the latter is interested in the efficiency of HVAC systems for multifamily midrise buildings. To carry out the credit requirements in the Indoor Environmental Quality category, ASHRAE standards that are specified for various mechanical building components should be followed. Certain modelling principles of heating and cooling distribution systems are also defined. For the categories that have just one credit applicable to BIM-based tools, “Water Efficiency” addresses calculating water used by all appliances in the building and having an idea about the billing information. Another category called “Material and Resources” have the credit that requires using environmentally preferable building components which are modelled using BIM-based tools. Lastly, “Regional Priority” credits are specifically listed for location of each project and the list for the case study building in the USGBC website includes two credits that can be achieved by energy analysis tools.

5.3. Overview of the Results – Examination of the LEED Credits

For Multifamily Midrise rating system in LEED v4, 46 credits including 17 prerequisites are reviewed within the scope of this thesis. 17 credits including 5 prerequisites (i.e., 37 % of the total credits) can be performed completely or partially by using Revit 2018, eQUEST v3.65, EnergyPlus v8.9 and IES-VE 2018. Besides, 58 points out of 110 points can be collected by using these four tools. While Revit seems to be the most successful BIM tool for LEED analysis by performing 15 credits that are equal to 58 points, eQUEST may be considered as the least effective BIM tool with just 10 credits that correspond to a total of 18 points. Nevertheless, this kind of comparison can be misleading since each tool have their own special features. Therefore, a more detailed comparison is needed as provided in the following sections.

5.4. Flowcharts

Based on the examination of the BIM-based energy analysis and design tools on the LEED credits, four flowcharts were developed to assist various construction professionals in the LEED process. In each flowchart, LEED credits that correspond to the processes from the design until the operation phase are associated with the related BIM-based tools that are investigated in this study. Although some parts of these flowcharts show a few overlaps, the flowcharts are essentially prepared to represent the different perspectives of multiple parties involved in the construction processes. These parties include: (1) contractors, (2) designers and architects, (3) MEP personnel, and (4) energy assessors and consultants who make decisions about LEED-compliancy and sustainable building designs using BIM-based tools. Flowcharts are presented in detail in the following paragraphs. Abbreviations in the flowcharts are as follows: “Re” for Revit, “eQ” for eQUEST, “EP” for EnergyPlus, and “I-V” for IES-VE.

For contractors

This flowchart given in Figure 5.1 is not only for contractors but also can be used by engineers and site managers. It focuses on the structural and mechanical works performed at sites and provides ideas on which BIM-based tools can be used during the performance of these works. 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.

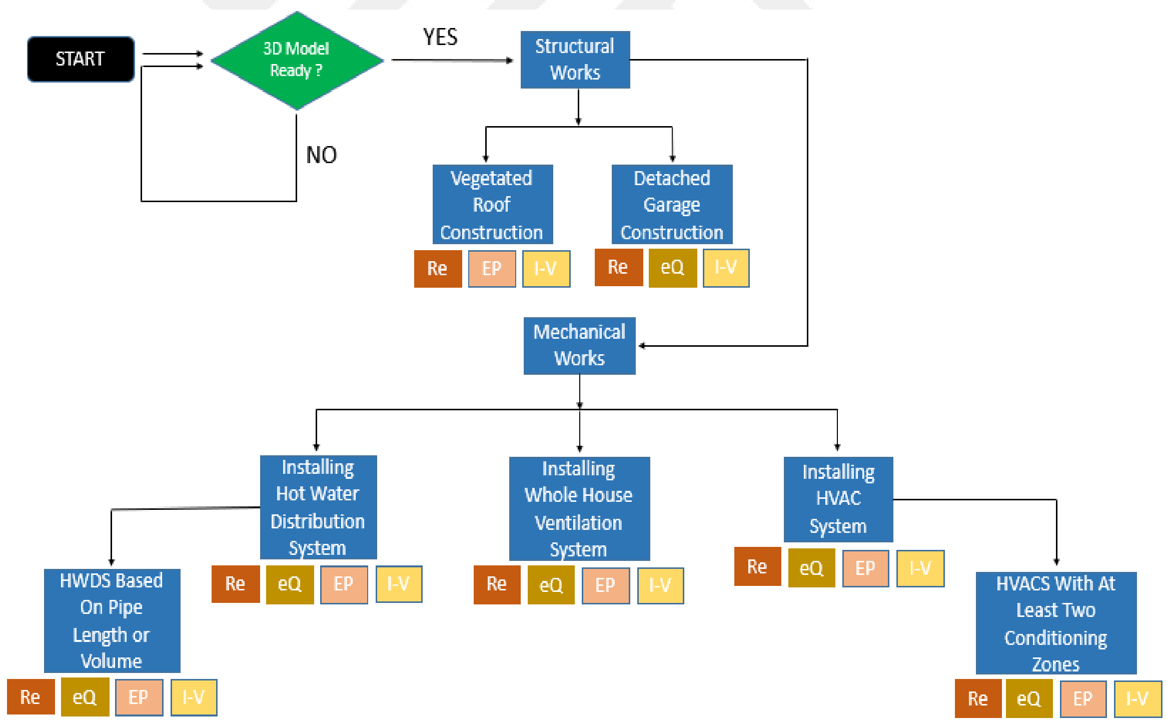


Figure 5.1 Flowchart-1 for contractors

The 3D model of the building may not be available as working with 2D drawings is still the dominant 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 is used in the modelling of the case study building, or else.

During the green roofing and garage construction, both Revit and IES-VE may be utilized by the contractors. 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 and whole house ventilation systems. Contractors would make use of the support of BIM during positioning and installation of such large and complex mechanical components. All four tools (i.e., Revit, eQUEST, EnergyPlus and IES-VE) have features that may be utilized for each of these mechanical work processes that are shown in Figure 5.1 above. For example, calculations related to the hot water distribution systems can be made based on either pipe length or volume by using all the tools. Additionally, an HVAC system with at least two conditioning zones can be installed by the tools investigated in this thesis.

For designers and architects

Second flowchart offers two paths to the users in the design phase (Figure 5.2). The decision here is made at the first step, and it is the decision of complying with ASHRAE. If ASHRAE compliance is needed (i.e., if the answer is “YES”), the first option is to use the ASHRAE 62.2-2010 standard that is necessitated for the credits such as “Air Filtering” and “Enhanced Ventilation”. eQUEST and IES-VE provide compliance for these standards and can therefore help the designers. 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.

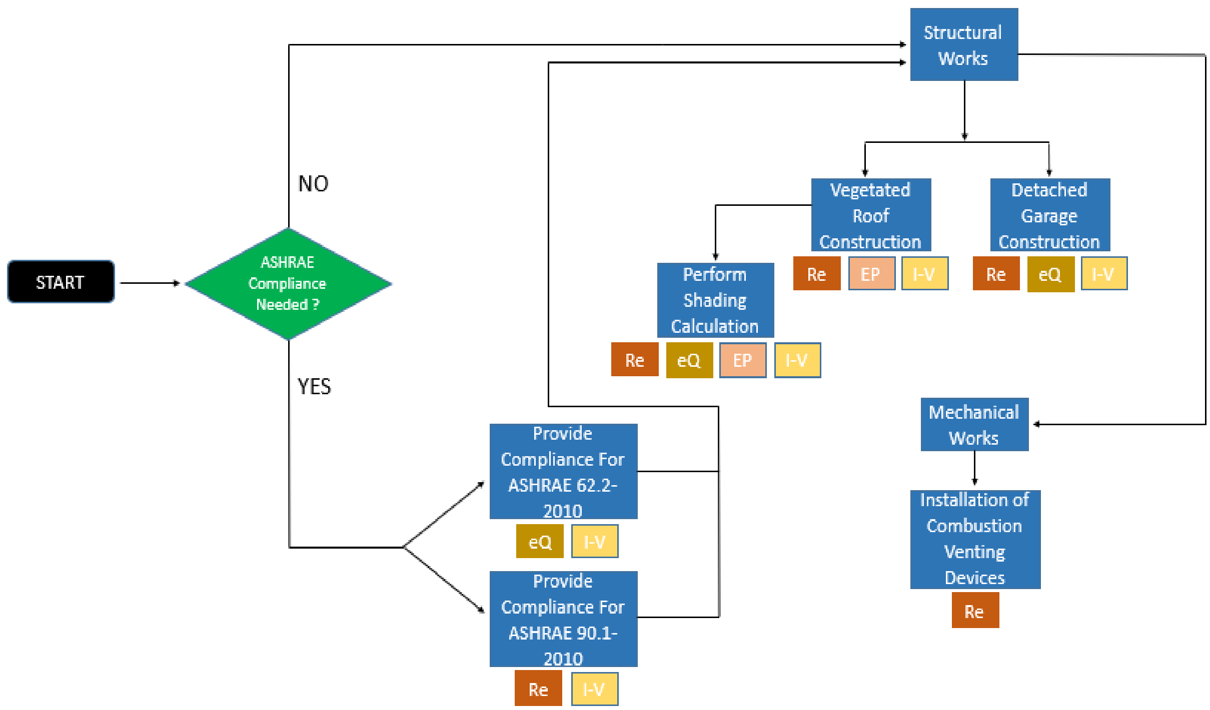


Figure 5.2 Flowchart-2 for designers and architects

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 the structural works. In addition to the structural works explained in the first flowchart, green roof that improves the shading performance of the building can be designed by designers or architects. In this step all the tools except eQUEST is helpful. But to go on with the shading calculations, all four tools (i.e., Revit, eQUEST, EnergyPlus and IES-VE) may be utilized. Lastly, the 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.

For MEP personnel

Flowchart number 3 was created to assist MEP personnel at certain stages of the mechanical works once the structural works have been completed. These processes include installing mechanical building components and providing compliance for building energy assessment certifications (Figure 5.3).

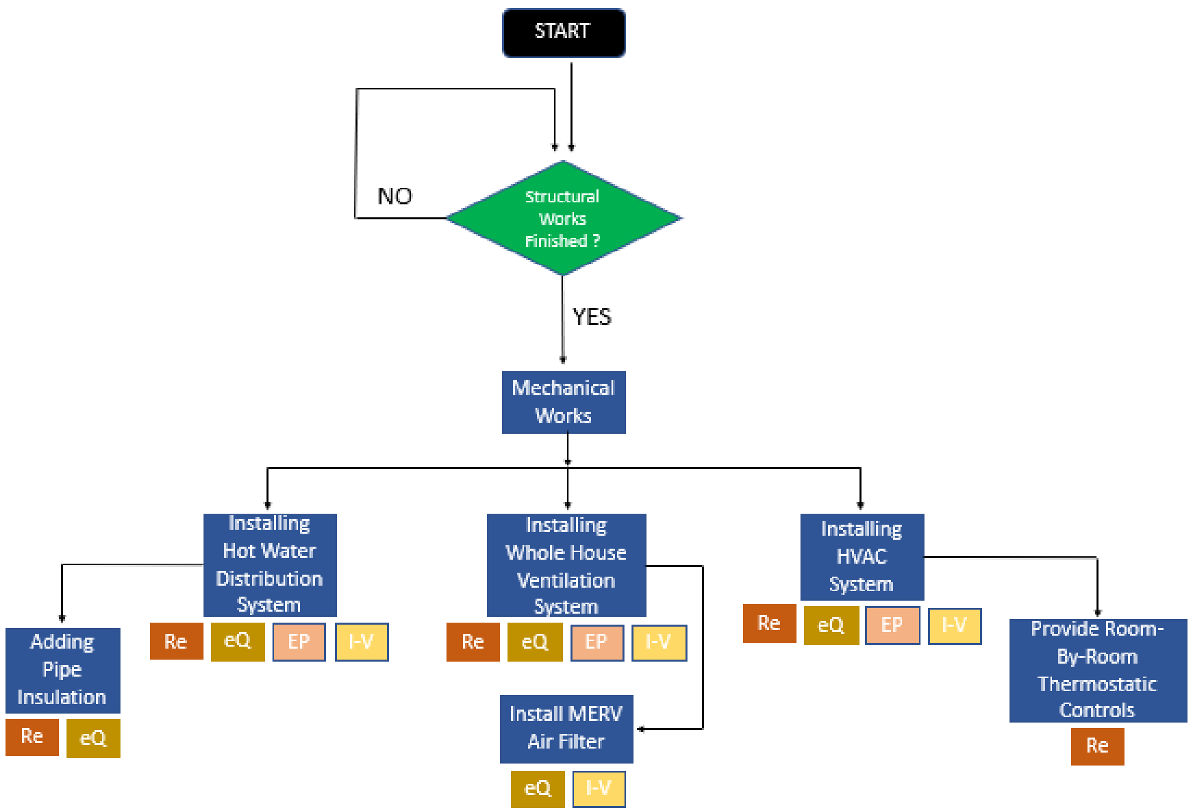


Figure 5.3 Flowchart-3 for MEP personnel

If the answer to the first question is “YES” (i.e., structural works are completed), the flowchart proceeds with the mechanical works. As it was stated in the first flowchart, all four tools may be used during the installation of hot water distribution, whole house ventilation and HVAC systems. 3 extra credits may be achieved by the MEP personnel using BIM-based tools related to these mechanical systems mentioned above. While both Revit and eQUEST may be used for adding insulations to pipes, 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 used for reducing allergens and providing an energy efficient HVAC system. MERV is designed by ASHRAE to measure the effectiveness of an air filter.

For energy assessors and LEED consultants

Last flowchart is designed to assist the energy assessors, LEED consultants or firms and/or individuals who offer green building certification system consultancy (Figure 5.4).

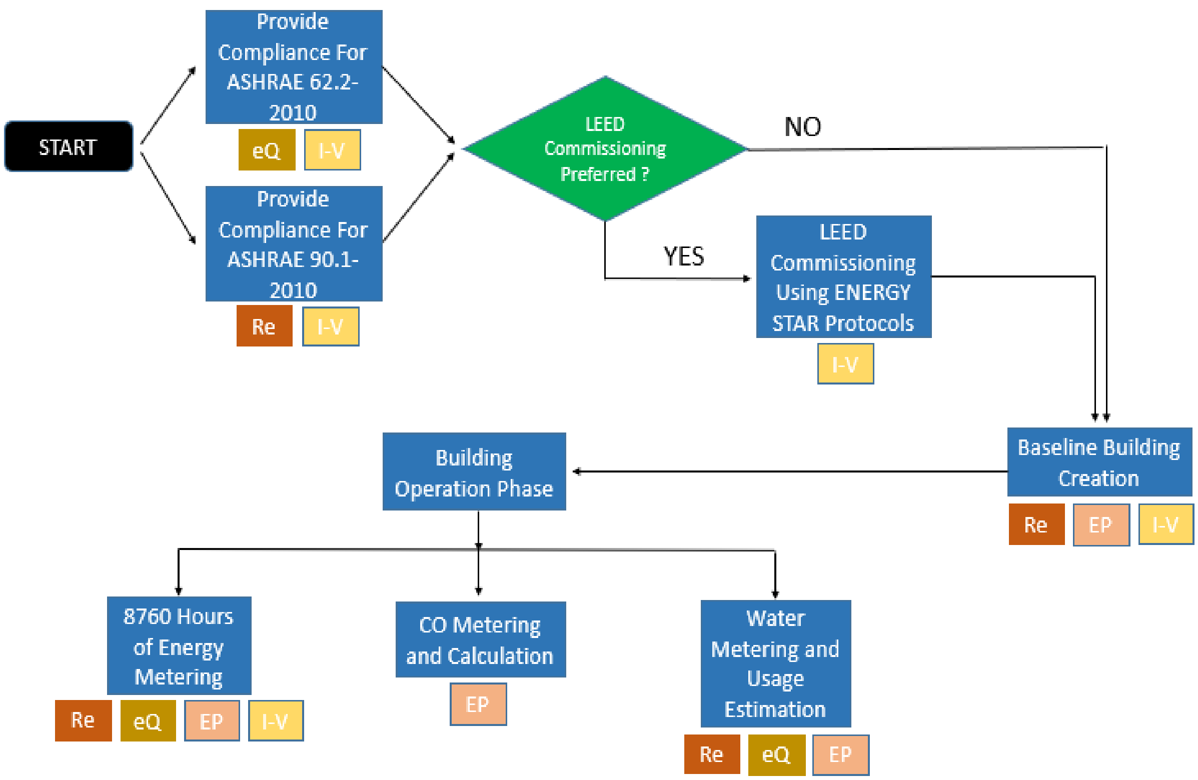


Figure 5.4 Flowchart-4 for energy assessors and consultants

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, EnergyPlus and IES-VE can be used to create a baseline building according to 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 a 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.

Information provided in the flowcharts are also summarized in table format in Table 5.1 below. This table lists the capabilities of the BIM-based tools in terms of the LEED credits based on the related project phases, and the intended users of the flowcharts as described in the above paragraphs. Project phases and the related credits are shown in the table. 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. As is the case with the flowcharts, this summary table aims to assist professionals to decide which tool to use during the LEED certification process.

Table 5.1 Capabilities of BIM-based tools and intended users based on project phases.

Project Phase[1]	Credit Name	Revit	eQUEST	Energy Plus	IES-VE	Users[2]
P1	Provide Compliance for ASHRAE 62.2-2010		✓		✓	D/A/EA/CNS
	Provide Compliance for ASHRAE 90.1-2010	✓			✓	D/A/EA/CNS
	LEED Commissioning Using ENERGY STAR Protocols				✓	EA/CNS
P2	Installing Hot Water Distribution System	✓	✓	✓	✓	CNT/MEP
	HWDS Based on Pipe Length or Volume	✓	✓	✓	✓	CNT
	Adding Pipe insulation	✓	✓			MEP
	Installing Whole House Ventilation System	✓	✓	✓	✓	CNT/MEP
	Installing HVAC System	✓	✓	✓	✓	CNT/MEP
	HVACS With At Least Two Conditioning Zones	✓	✓	✓	✓	CNT
	Provide Room-By-Room Thermostatic Controls	✓				MEP
	Installation of Combustion Venting Devices	✓				D/A
	Baseline Building Creation	✓		✓	✓	EA/CNS
	Detached Garage Construction	✓	✓		✓	CNT/D/A
	Vegetated Roof Construction	✓		✓	✓	CNT/D/A
	Perform Shading Calculation	✓	✓	✓	✓	D/A
	Install MERV Air Filter		✓		✓	MEP
P3	8760 Hours of Energy Metering	✓	✓	✓	✓	EA/CNS
	Water Metering and Usage Estimation	✓	✓	✓		EA/CNS
	CO Metering and Calculation			✓		EA/CNS

[1] P1 = Design, P2 = Construction, P3 = Operation
[2] CNT = Contractor, D = Designer, A = Architect, MEP = MEP Personnel, EA = Energy Assessor, CNS = Consultant

As can be seen from the table, various LEED certification measures offered by each BIM-based tool are related to the three main project stages (i.e., design, construction and operation). Revit and IES-VE provides the highest support among all BIM-based tools according to the findings of this study. Contractors, energy assessors and consultants would make more use of the investigated BIM-based tools than the other project participants. Finally, it is identified that most of the contribution of the BIM-based tools in LEED certification process is to the mechanical works with 9 achievable credits. While it is observed that the support of the tools in the construction phase is more significant; there are only 3 achievable credits by using the BIM-based tools in the building operation phase. To increase the support of the BIM-based tools in the LEED certification process, more information regarding the building project must be collected, such as site layout and logistics.

CHAPTER VI

DISCUSSION

6.1. Pros and Cons of BIM-based Tools for LEED Credits

In this section, the capabilities of the BIM-based tools are explained, and the tools are compared. Key advantages and disadvantages of using the four BIM-based tools (i.e., Revit, eQUEST, EnergyPlus and IES-VE) are discussed by listing twelve achievable LEED credits. Other five achievable LEED credits that are not included in this list are not reflecting the special features of BIM-based tools, because all those five credits, except the "Regional Priority" credit, can be completely or partially achieved by all of the four BIM-based tools. Regional Priority credit, on the other hand, has requirements that are not directly related with the features of BIM-based tools.

1. **Heat Island Reduction:** Even though eQUEST can fulfil the requirements of this credit with shading calculations, it cannot model vegetated roofing / green roof as opposed to the other tools.
2. **Rainwater Management:** Only eQUEST does not have the feature of modelling vegetated roofing / green roof that can be related to the rainwater management. On the other hand, IES-VE is the only tool to calculate 95^{th} / 98^{th} percentile rainfall event to check on-site management of water.
3. **Nontoxic Pest Control:** Due to their advanced modelling features, Revit and IES-VE are capable of adding openings to the building design for MEP components and

various concrete walls as below-grade walls to help with nontoxic pest control in the building.

4. **Water Metering:** Among the four BIM-based tools, IES-VE is the only one that does not have the ability to perform water metering.
5. **Minimum Energy Performance:** Revit and IES-VE can provide compliance for ASHRAE 90.1-2010 standards to meet the requirements of the baseline building performance. Additionally, IES-VE has the privilege of undertaking commissioning for LEED projects amongst the four BIM-based tools.
6. **Annual Energy Use:** Unlike Revit, EnergyPlus and IES-VE, eQUEST is not capable of creating a baseline building according to ASHRAE 90.1-2010 standards. eQUEST can only provide the annual energy use information.
7. **Efficient Hot Water Distribution System:** All four BIM-based tools can fulfil the first requirement of this credit. In addition to that, Revit and eQUEST can also add at least R-4 pipe insulation on the domestic piping system.
8. **Combustion Venting:** EnergyPlus can only fulfill this credit since carbon monoxide is metered and calculated in terms of mass and volume based on emission factors.
9. **Air Filtering:** Only eQUEST and IES-VE have the ability to install air filters with MERV of 8 or higher per ASHRAE 62.2-2010 standards.
10. **Balancing of Heating and Cooling Distribution Systems:** Revit is the only tool to model the flow-control valve for every radiator in the building that will help with the balancing of heating and cooling distribution systems.

11. **Enhanced Combustion Venting:** Considering all tools examined in this study, only Revit can model combustion devices like fireplace and woodstove.
12. **Enhanced Garage Pollutant Protection:** Among the four BIM-based tools, EnergyPlus is the only one that cannot model a parking garage.

6.2. Interpretations

The findings of this thesis demonstrate that the BIM-based tools can contribute to the LEED certification process and help construction professionals while developing sustainable and energy-efficient building designs. For the purpose of limiting excessive energy consumption, building performance measurements are being done regularly. Usage areas of BIM applications and 3D analysis tools are expanding in order to develop sustainable building designs according to the related standards (Muller 2014). As it was expected in the beginning of thesis study, outcomes of the research on LEED credits indicated that Revit is the most advantageous BIM-based tool having the most achievable LEED credits. However, this outcome does not necessarily signify that Revit is the best BIM-based tool among the four tools (i.e., Revit, eQUEST, EnergyPlus and IES-VE) in terms of energy efficiency analyses. Each BIM-based tool may have certain weaknesses or strengths from different environmental and performance aspects. These weaknesses or strengths are discussed in the Sections 4.6, 4.8, 4.10, 4.12, 5.4 and 6.1 of this thesis.

6.3 Constraints and Limitations

LEED is selected as the green building rating and certification system to be investigated in this study, and a residential building is used as the case study. LEED version

4 is utilized for examining the credits and a multifamily midrise residential building is used as the related rating system since the case study building has four or more occupiable stories above grade. The case study building is modelled in Revit, by using the 2D structural and architectural drawings as basis, and the MEP components are not included in the building model. Only BIM-based tools are used for the purpose of this study and the tools that are compatible with Revit are selected (i.e., eQUEST, EnergyPlus and IES-VE). These tools were selected because of being well-recognized tools that are commonly used and easily accessible for construction professionals.

One of the limitations of this study is to use the limited version of IES-VE during the process of examining the LEED credits. One-year student license was purchased for IES-VE. The student version has some limitations in terms of energy analysis features, and because of that, only the LEED credits that were available with the student 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 thesis.

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 2011). In some cases, certain credits, were not able to 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”. In a real case, each requirement of a credit must be fulfilled and verified.

CHAPTER VII

CONCLUSION

The goal of this thesis is to demonstrate in what ways BIM-based energy analysis and design tools can support construction project teams in pursuit of LEED certification for their projects. In accordance with this goal, this study is aimed to (1) investigate the support of BIM-based energy analysis and design tools during the LEED certification process, and (2) create flowcharts that can be used by various project participants for deciding which tool to use for what specific purposes during the LEED process. In accordance with the first objective, the details of LEED credits were investigated by utilizing BIM-based tools and reviewing their features that may be advantageous for achieving the LEED requirements. The requirements of LEED credits were investigated to identify whether they can be achieved by using BIM-based tools. For achieving the second objective, flowcharts were created with the intention of assisting various construction project participants and providing necessary information to decide on the appropriate BIM-based tool during LEED certification process.

A six-storey residential building was modelled in Autodesk Revit as the case study. Revit was first examined for LEED credits and thereafter the investigation on Revit was finished, 3D building model was exported to the other three BIM-based tools (i.e., eQUEST, EnergyPlus and IES-VE, respectively). Those four BIM-based tools were selected due to being commonly used and their well-known reputation in the AEC industry. The GBRCS that was investigated in the study was LEED v4, and the rating system of BD+C: Multifamily Midrise was examined. Main target group of the study involved contractors, engineers, site managers, designers, architects, energy assessors, LEED consultants and all other professionals who aim to receive and/or apply for a LEED certificate for their new buildings.

7.1. Contributions

This thesis reviewed the literature on BIM-based energy analysis and design tools and the LEED certification process. Assistance of BIM-based tools during compliance for LEED requirements and designing green buildings was investigated. Within the scope of the literature review, similar studies that were previously conducted were reviewed, and the most commonly used and well-known BIM-based tools were investigated.

Previously conducted studies mostly discussed the differences between the two well-known GBRCSs, namely BREEAM and LEED, in terms of their scoring systems and assessments of credits in the certification process. In some case studies, performance measurements of BIM-based tools were analysed in terms of different aspects, such as water, space heating, lighting, carbon emissions, and acoustics. By categorizing the credits of different GBRCSs, assessments that may be supported by BIM were identified. Also, different versions of ASHRAE standards were compared in terms of the effect on point scoring system of LEED. Literature review demonstrates that 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.

The work presented in this master thesis, on the other hand, reviews the most commonly used and well-known BIM-based tools while analysing the most recent version (v.4) of the LEED certification system. Credit-based examinations were performed in the

LEED certification process by reviewing each credit individually. Assistance of BIM-based tools suggested in this thesis have the potential to facilitate green building designs and making efficient resource-based decisions in the AEC industry. Thanks to the collaboration and interoperability capabilities of the BIM-based tools utilized in this study, one 3D building model created in Revit could be used with the rest of the three tools. As the result of the investigations on LEED credits, Revit may be seen as the most advantageous having the most achievable credits. However, flowcharts showed that each BIM-based tool may be utilized at different project stages for various purposes. As the major contribution of this thesis, four flowcharts that were created can support construction professionals in pursuit of not only LEED certification but also designing more energy-efficient buildings. These flowcharts are beneficial for fulfilling the design objectives that aim to promote sustainability and achieve LEED certification. This study was conducted to demonstrate the usage and support of BIM-based tools for building projects that intend to achieve LEED certification, and eventually to encourage BIM usage.

7.2. Implications & Recommendations

Findings of this study help exploring more about the GBRCSs and encourage next generations to use BIM-based tools for making more energy-efficient designs. In this regard, it is crucial to use renewable resources that reduce GHG emissions, promote recycling of material and better management of waste, and provide a healthy and safe environment. Extreme levels of energy consumption of buildings are being considered more than before due to its contribution to the climate change (Cramer 2017). Hence, energy performance measurements and related cost estimations are being adopted in the construction industry with the integration of BIM-based tools. Findings of this study demonstrate that BIM-based tools can contribute to the LEED certification process.

Although LEED and such GBRCSs promote sustainable designs and construction, it should be noted that LEED's role in reducing the construction industry's GHG emissions and contribution to the global warming is limited. Construction is globally accounted for the 36 % of the total energy use (Hasnan 2019), and construction is responsible for having the largest share of negative environmental impacts (Strandberg 2019). The main concerns have been the GHG emissions, excessive production of waste material, high energy consumption and other negative impacts to the natural environment. However, since most of the focus for reducing the GHG emissions in construction industry has been given to the operational stage of buildings, the embodied GHG emissions in projects have been overlooked. Since now the buildings are being designed to be more energy efficient, the impacts of embodied emissions have become more critical (Itard 2019). Embodied emissions are associated with the production of a building, including the extraction, manufacturing and transportation of construction materials, as well as the construction processes, that includes the initial construction of the building, but also major renovations and demolition stage (Dulmage and Mousa 2018). It is important to start focusing on reducing the embodied energy in construction, because although it depends on the types of materials used in construction, in some cases embodied energy can exceed the life cycle operational energy of certain types of buildings (Praseeda, et al. 2016). LEED is currently working on developing a newer version (v4.1) and changes are being applied to the Materials and Resources credits to more effectively address the embodied energy in buildings (Hughes 2019).

Considering the limited natural resources, project participants should be aware of the negative environmental impacts of construction in all stages, and therefore, take necessary actions accordingly through the lifecycle of buildings. Energy performance of buildings can be analysed and improved through BIM applications with the intention of minimizing energy consumption and preserving natural resources. Significance of constructing green buildings that are less destructive to the environment should be acknowledged in near future, only then, construction waste can be reduced, and natural habitats are protected. Also, green building concept should be integrated into the education system in the universities in order to raise awareness on the environment for future engineers and designers.

7.3. Future Work

Conducted study presented in this thesis demonstrating the integration of BIM with LEED certification can further be improved by including the cost analysis aspect. A building project that is handled throughout its lifecycle by considering the expenditures of LEED certification process can be studied as a future work. Related cost analysis during the fulfilment of the LEED requirements can present a more comprehensive approach.

Furthermore, investigations on LEED credits can be extended by including mechanical building components in the 3D building model. In addition to the architectural and structural elements included in the building model for this thesis, mechanical building components can also be modelled in order to examine MEP-related credits in more detail. In order to generalize the results of this thesis, an approach similar to that presented in this study can be followed to implement BIM-based LEED analysis on different types of projects (i.e., hospital, schools and retail).

“Location and Transportation” category in LEED v4 BD+C: MM rating system may be further analysed in more detail. As seen in some recent related studies, three “Location and Transportation” credits, namely Site Selection, Community Resources and Access to Transit may be achieved using Dynamo in Revit. In addition to that, the credit from the “Innovation” category may be achieved with further exploration of BIM to assess design alternatives.

Finally, as future work, the support of BIM-based tools for the newer versions of LEED can be studied. Particularly, contributions of the BIM-based tools in reducing the embodied emissions of projects can be investigated with the upcoming version of LEED (LEED v4.1).

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VITA

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