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Case study for comparative analysis of BIM-based LEED building and non-LEED building

BIM tabanlı LEED binası ile LEED olmayan binanın karşılaştırmalı analizi için vaka çalışması

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Abstract

The objective of this study is to design a sustainable high-rise residential building using Leadership in Energy and Environmental Design (LEED) and Building Information Modeling (BIM) and perform comparative analysis for the LEED building and non-LEED building. In this scope, the additional cost related to water and energy efficient systems and the additional total cost for the LEED building were analyzed to calculate the respective break-even points. The research methodology relies on the literature review and case study. In the case study, the 3D model of a 15-storey residential building was designed via Autodesk Revit 2019 based on the LEED v4.1 Building Design and Construction (BD+C) rating system. The case study building can achieve 31 credits and 9 prerequisites which allow to obtain 61 points and LEED Gold certificate. By applying LEED v4.1 BD+C procedures, water consumption of the building was reduced by 65.96%, and energy consumption of the building was decreased by 59%. The initial cost of LEED building is 1,074,833.04 TL which is 852,230.64 TL higher than the initial cost of non-LEED building. According to the break-even point calculations, the additional total cost of LEED building can be charged after 13 years 8 months and 12 days. Results make a significant contribution to the literature and industry by showing the requirements and design process of a high-rise residential building using LEED and BIM. This study adds original value to the literature and industry by ensuring practitioners and researchers with constructive information about the energy, water, and cost performance of LEED buildings. Further, results provide an insight to professionals in the architecture, engineering, and construction industry about the value of green buildings.

Keywords: LEED, BIM, Building information modeling, Green building, Sustainable residential building, Break-even point.

Öz

Bu çalışmanın amacı, Enerji ve Çevre Tasarımında Liderlik (LEED) ve Yapı Bilgi Modellemesi (BIM) kullanarak sürdürülebilir yüksek katlı bir konut binası tasarlamak ve LEED binası ve LEED olmayan bina için karşılaştırmalı analiz yapmaktır. Bu kapsamda, su ve enerji verimli sistemlerle ilgili ek maliyetler ve LEED binası için toplam ek maliyet analiz edilerek ilgili başabaş noktaları hesaplanmıştır. Araştırma yöntemi, literatür taraması ve vaka çalışmasına dayanır. Vaka çalışmasında, 15 katlı bir konut binasının üç boyutlu modeli, LEED v4.1 Bina Tasarım ve İnşaat (BD + C) derecelendirme sistemine dayalı olarak Autodesk Revit 2019 aracılığıyla tasarlandı. Vaka çalışması binası, 61 puan ve LEED Gold sertifikası elde etmeyi sağlayan 31 kredi ve 9 önkoşul sağlayabilir. LEED v4.1 BD+C prosedürleri uygulanarak, binanın su tüketimi %65.96'ya, binanın enerji tüketimi ise %59'a kadar azaltılmıştır. LEED binasının başlangıç maliyeti 1,074,833.04 TL olup, LEED olmayan binanın başlangıç maliyetinden 852,230.64 TL daha fazladır. Başabaş noktası hesaplamalarına göre, 13 yıl 8 ay 12 gün sonra LEED binasının toplam ek maliyeti tahsil edilecektir. Sonuçlar, yüksek katlı bir konut binasının gereksinimlerini ve tasarım sürecini LEED ve BIM kullanarak sunup literatüre ve sektöre önemli katkı sağlar. Bu çalışma, uygulayıcılara ve araştırmacılara LEED binalarının enerji, su ve maliyet performansı hakkında yapıcı bilgiler sağlayarak literatüre ve sektöre özgün bir değer katmaktadır. Ayrıca, sonuçlar mimarlık, mühendislik ve inşaat sektöründeki profesyonellere yeşil binaların değeri hakkında fikir vermektedir.

Anahtar kelimeler: LEED, BIM, Yapı bilgi modellemesi, Yeşil bina, Sürdürülebilir konut binası, Başabaş nokta.

1 Introduction

The architecture, engineering and construction (AEC) industry, which produces nearly 1/3 of the global greenhouse gas emissions, is among the primary sectors in terms of global warming [1]. The building sector is responsible for 40% of the global energy and global resource consumption [2]. The U.N. Environment and International Energy Agency (2017) stated that developed and developing countries cause carbon emissions of 50-100 tons of CO_2/ terajoule (e.g., Canada, Russia, Brazil, Argentina, and Algeria), 100-150 tons of CO_2/terajoule (e.g., USA, Mexico, Kazakhstan, North Korea, and China) and over 150 tons of CO_2/terajoule (e.g., Australia, Indonesia, India, Malaysia, and Bahrain) [3]. According to these results, this data is much above the targeted value because the energy-carbon

densities of existing buildings should be no more than 20 tons of CO_2 per terajoule [3]. This is a significant indication that global temperature will rise more than 2 °C by 2050 [1]. Hence, carbon capture, utilisation, and storage are included in the purpose of net zero-carbon emissions by 2050. Considering the global climate targets described in the Paris Agreement, a 30% improvement in energy use per square meter of buildings is required by 2030 to reduce the high carbon emissions caused by buildings and construction industry [1]. Due to the increasing awareness of environmental concerns, the AEC industry has been recently shifting to the green buildings which are defined as high-performance sustainable buildings. The purpose of a green building (GB) is to preserve energy, water, materials, and land during its life cycle, and provide healthy environments for its occupants by applying sustainability

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principles [4],[5]. These principles are to decrease resource consumption, reuse resources, utilize recyclable resources, conserve nature, remove toxics, employ life-cycle costing, and address quality [6].

Green building rating systems (GBRSs) are developed to promote and contribute to the green buildings, and increase their market value. Green building rating systems are validated, and scalable guidelines for implementing sustainability requirements to the built environment through design, construction, and operation decisions for buildings as well as neighborhoods and cities [7]. The purpose of GBRSs is to score or rate the environmental, resource, and health impacts of a building's design, construction, and operation against the criteria within the scope of the assessment system. In line with this purpose, GBRSs provide information to the design teams for solving problems about environmental issues. Further, GBRSs ensure verifiable and reasonable criteria and goals for reaching higher environmental standards in the building design, construction, and operation [8]. Accordingly, GBRSs assist practitioners to evaluate the building performance and fulfill the requirements of sustainable design and construction [7].

Sustainable design is defined as the "conception and realization of ecologically, economically, and ethically responsible expression as part of the evolving matrix of nature" [9]. Sustainable construction is described as "creating and operating a healthy built environment based on resource efficiency and ecological design" [10]. Sustainable construction projects designed considering the GBRSs require multiple technical disciplines which have increased levels of interdependency and interconnectedness [4],[5].

Building Information Modeling (BIM) provides an integrated platform to fulfill the arduous requirements of GBRSs-based sustainable design and construction efficiently. BIM enables three-dimensional digital representation of a facility and its processes [11]. According to the United States national BIM standard (NBIMS-US), BIM provides to perform engineering analysis, conflict analysis, code criteria checking, cost engineering, as-built product, and budgeting for a facility. Studies show that using BIM in the design, construction, and operation processes of GBRSs-based buildings promotes sustainable design and construction, helps reduction of carbon footprint, streamlines the green building certification process, and therefore supports the economy [12]-[14].

This study aims at (1) designing a sustainable high-rise residential building using Leadership in Energy and Environmental Design (LEED) v4.1 Building Design and Construction (BD+C) and Building Information Modeling (BIM) and (2) performing comparative analysis for the LEED building and non-LEED building. Within this scope, the additional cost related to water and energy efficient systems and the additional total cost for the LEED building were analyzed to calculate the respective break-even points. In this paper, non-LEED building refers to the conventional building, the former version of the case study building, which was designed without addressing sustainability principles. On the other hand, LEED building refers to the case study building which was redesigned according to the LEED v4.1 BD+C rating system requirements. The major contribution of this research is to present (1) the requirements and design process of high-rise residential buildings using LEED and BIM, and (2) the differences in energy and water consumptions, and total cost between LEED and non-

LEED residential buildings. Practitioners in the BIM–based sustainable construction projects would benefit from the results of this research.

2 Literature review

In the literature review, studies addressing (1) green building rating systems (GBRSs), (2) the use of BIM in the GBRSs based sustainable construction projects, and (3) comparison of LEED and non-LEED buildings were investigated.

2.1 Green building rating systems:

Several international and national GBRSs exist in the AEC industry. Some of the prominent GBRSs are BREEAM (Building Research Establishment Environmental Assessment Method), LEED (Leadership in Energy and Environmental Design), DGNB (Deutsche Gesellshaft fur Nachhaltiges Bauen (German Sustainable Buildign Council)), Energy Star, Green Star, Green Globes, and CASBEE (Comprehensive Assessment System for Built Environment Efficiency). Even though the GBRSs are different, they have similar purposes including assessment of building environmental performance and efficient use of natural resources such as land, water, and, energy.

Among the GBRSs, LEED developed by the US Green Building Council is the most widely applied international green building rating system around world [10],[15]. More than 79,000 projects achieve LEED certification in the last two decades [16]. LEED can be applied to various building types including commercial office, retail, school, healthcare, and single- and multi-family housing settings. For these reasons, LEED was used as a GBRS to design a sustainable high-rise residential building in this study.

In the last version of LEED (i.e., LEED v4.1) eight categories exist which are Location and Transportation, Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, Innovation, and Regional Priority. Each category includes relevant prerequisites and credits. In order to gain the LEED certification for a building/project, a number of prerequisites and optional credits should be achieved [7]. While the prerequisites do not provide any point, the achievable points from a single credit vary from 1 to 20 in the LEED v4.1. The level of LEED certification is determined by the number of credits and associated points a building/project achieves. A building can be certified by LEED according to the following certification levels and relevant points: (1) Certified (40-49 points), (2) Silver (50-59 points), (3) Gold (60-79 points), and (4) Platinum (80+ points).

With the aim of achieving the GB certification for a building/project, first, the appropriate credits should be chosen to be met in the project from a large set of credits categorized under the selected GBRS. Then, the requirements of these selected credits should be fulfilled by the project teams. For this reason, selecting credits is a crucial decision to accomplish the sustainability objectives of the building/project [4],[5]. An interdisciplinary work is required to qualify the sustainable performance of the building/project This process could be compelling, arduous, and time-consuming [17].

2.2 Integrating BIM and GBRSs:

BIM provides a digital platform to maintain graphic information and material properties concerning the building elements that in turn declines the time and effort required to analyze building

data [18]. Hence, BIM ensures practitioners to deal with the increased levels of interdependency and interrelatedness among different disciplines in the GBRS-based sustainable design and construction [17],[18]. Some studies addressed BIM-based sustainable design and construction considering different GBRSs. One of the studies on this topic focused on measuring the performance of BIM-based tools (i.e., Autodesk Revit and IES-VE) on the LEED v2.2 certification process [12]. A study conducted by Lu et al (2017) addressed fourteen BIM software and their functions for LEED v3 based green buildings to analyze energy, carbon emissions, natural ventilation, daylighting, and acoustics performance [14]. In another study, a BIM software (i.e., Autodesk Revit) was used for fulfilling the requirements of the Sustainable Building Tool in Portuguese [19]. A more recent study performed by Ansah et al (2019) reviewed the literature for evaluating the contributions of BIM for LEED, BREEAM, BEAM Plus, and, CASBEE [14]. Similarly, Doan et al (2017) examined the utilization of BIM for Green Star in New Zealand by performing literature review, semi-structured interviews, and content analysis via NVivo 11 [20]. More recent studies on this subject domain focused on integrating biophilic criteria into green building rating tools using Green Mark and LEED v4 [21], existing opportunities for population health promotion within LEED v4 [6], and the trade-off between time, cost, and sustainability represented in LEED v4 credits using a genetic algorithmic model [22]. Although some scholars analyzed the use of BIM in the GBRS-based sustainable design and construction over the last decade, only a few of them have examined BIM for the earlier versions of LEED. In addition, none of these studies addressed designing sustainable high-rise residential buildings. Hence, in this research BIM (i.e., Autodesk Revit 2019) was utilized for designing a sustainable high-rise residential building based on the LEED v4.1 BD+C rating system.

2.3 Comparing LEED and non-LEED buildings

When studies on comparing LEED and non-LEED buildings are reviewed, results show that researchers mainly focused on energy performance [23], occupant satisfaction [24]-[27], and health and safety [28],[29]. The study of Fortuna III et al. (2012) identified the safety risks for high-performance sustainable construction projects by performing six detailed case studies and two validation case studies [29]. In another research, Altomonte and Schiavon (2013) compared LEED certified buildings and non-LEED rated buildings by evaluating a subset of the Center for the Built Environment Occupant Indoor Environmental Quality Survey database which cover 144 buildings and 21,477 individual occupant responses [24]. A follow-up study of Schiavon and Altomonte (2014) addressed analyzing the impact on user satisfaction in LEED and non-LEED certified buildings of factors which are unrelated to the environmental quality such as spatial layout, distance from window, and building size [25]. In a more recent study, Amasyali and Gohary (2016) analyzed the energy-related values and satisfaction levels of 618 residential and office building occupants in Arizona, Illinois, and Pennsylvania [26]. Another recent study conducted by Jeong et al (2016) presented an assessment process with the aim of comparing the green and non-green buildings' energy performance. For this purpose, the building attributes and energy consumption of 455 multi-family housing complexes were analyzed through data mining [23].

According to the literature review results, even though some researchers examined the discrepancies between LEED and non-LEED buildings and/or green and non-green buildings, none of them calculated the break-even points of water and energy efficient systems and additional total cost for the LEED buildings. The break-even point refers to the point where the balance between cost and income is achieved. In accordance, the break-even points of water and energy efficient systems utilized for the LEED building provide a beneficial insight to the AEC professionals about the value of green buildings. In this research, a sustainable high-rise residential building is designed using LEED v4.1 BD+C and BIM (i.e., Autodesk Revit), and the additional cost related to water and energy efficient systems and the additional total cost for the LEED building were analyzed to calculate the respective break-even points.

3 Methodology

The research methodology of this study includes a literature review and a case study. Literature review allows to collect information, criticize previous studies, and determine the key points in the research field. Accordingly, more generalized results can be produced by reviewing the literature [30],[31]. On the other hand, case study helps to detect specific problems, if any, and capture detailed information on the subject matter [32]. Thus, these two research methods support each other that in turn enrich the outputs of the study. The research methodology of this study is provided in Figure 1.

3.1 Literature review

Within the scope of the literature review, studies that were published between 2007 and 2020 were investigated. For this purpose, Web of Science core collection database and Scopus were utilized. Articles, conference proceedings, scientific reports, and books were included in the review. The keywords used in this research are building information*, BIM, BIM-based sustainable*, BIM-based green*, BIM-based energy efficient*, non-LEED*, non-green*, LEED*, energy efficient building*, sustainable building*, green building*, green building rating*, green building assessment*, and green building certification*. Each publication was reviewed to select the appropriate data source.

3.2 Case study

In the case study, the 3D model of a sustainable high-rise residential building was redesigned via Autodesk Revit 2019 based on the LEED v4.1 Building Design and Construction (BD+C) rating system. LEED BD+C is selected as the rating system since it is developed for buildings which are newly constructed or under major renovation. In this research, the building type is chosen as a residential building because studies prove that between 1971 and 2004, CO_2 emissions is estimated to have elevated by 1.7% per year due to residential buildings [10].

Autodesk Revit is preferred for the modelling of the case study building because this software is a well-accepted BIM tool. Modelling was performed using the 2D.dwg files of the case study building. Architectural and structural building components were included in the 3D model while mechanical building components, fixtures, and heating/cooling distribution systems (i.e., MEP (mechanical, electrical and plumbing)) were not included in the 3D model. The case study building is a 15-floor residential building which consists of two basement floors, a ground floor, and twelve identical floors. Its construction area is 5685 sqm, floor height is 2.9 m, and green area is 3700 sqm.
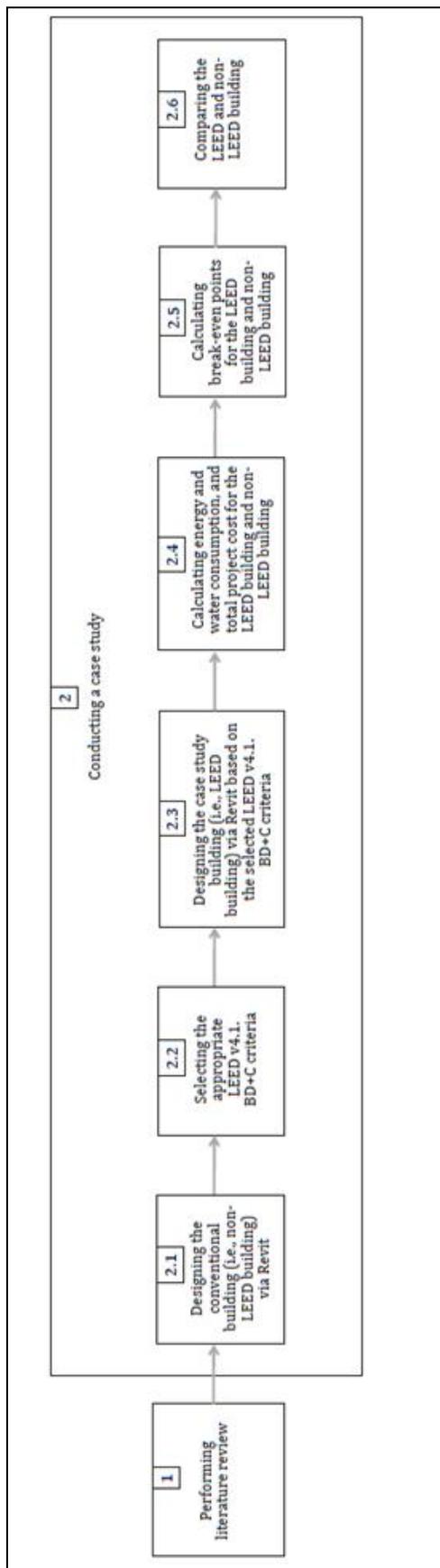
Figure 1. Research methodology.

The building is located in Kadikoy, Istanbul. Render of the 3D model for the case study building is given in Figure 2. Total cost for finishing works, energy and water consumptions, and related expenses of the LEED building (i.e., case study building) and non-LEED building were calculated via MS Excel.
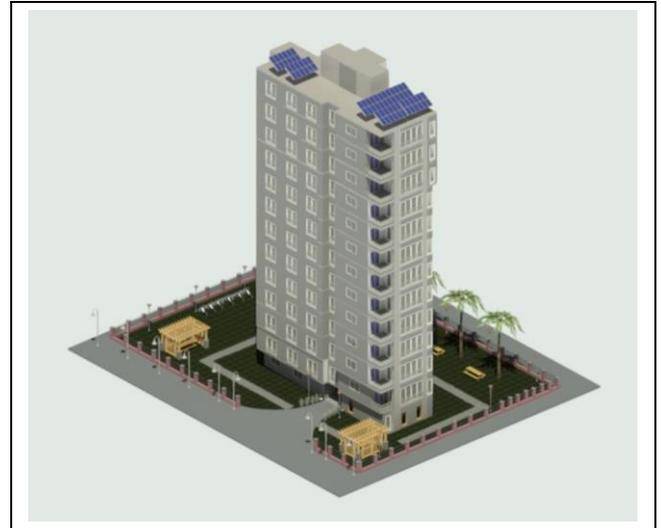

Figure 2. Render of the 3D model for the case study building

4 Application of LEED in the BIM-based building design

Sustainability principles are accomplished in the case study building by applying requirements of 31 credits and 9 prerequisites in the LEED v4.1 BD+C rating system. Therefore, the case study building can achieve 61 points and LEED Gold certificate. In fact, according to the LEED procedure, the prerequisites are must; thus, all of them should be performed within the scope of the building/project. However, in this case study, two prerequisites in the *Energy and Atmosphere* category, which are (1) *fundamental commissioning and verification* and (2) *minimum energy performance*, could not be fulfilled due to the lack of MEP drawings.

4.1 Location and transportation

The purpose of *Location and Transportation* is to ensure occupants a more sustainable environment by decreasing land use and CO_2 emissions resulted from transportation [33]. In this category, the requirements of *sensitive land protection, high-priority site and equitable development, surrounding density and diverse uses, access to quality transit, bicycle facilities, reduced parking footprint,* and *electric vehicles* were met in the case study building. Therefore, 13 points out of 16 points can be earned.

4.2 Sustainable sites

The purpose of *Sustainable Sites* is to ensure that a project's natural environment would be valued and respected throughout the building project delivery process [33]. In this category, the requirements of *construction activity pollution prevention (prerequisite), site assessment, protect or restore habitat, open space, rainwater management, heat island reduction,* and *light pollution reduction* were fulfilled in the case study building. Accordingly, 10 out of 10 points can be obtained.

4.3 Water efficiency

The purpose of *Water Efficiency* is to minimize water consumption in the project by pursuing water use reduction strategies and considering non-potable and alternative sources of water [33]. In this category, the requirements of *outdoor water use reduction (prerequisite), indoor water use reduction (prerequisite), building level metering (prerequisite), outdoor water use reduction, indoor water use reduction, cooling tower water use,* and *water metering* were performed in the case study building. Thus, 10 out of 11 points can be received.

4.4 Energy and atmosphere

The purpose of *Energy and Atmosphere* is to minimize the use of fossil fuels and promote better building energy performance by conducting innovative strategies [33]. In this category, the requirements of *building-level energy metering (prerequisite), fundamental refrigerant management (prerequisite), advanced energy metering,* and *renewable energy* were met in the case study building. Therefore, 6 out of 33 points can be gained.

4.5 Material and resources

The purpose *of Material and Resources* is to mitigate the embodied energy and other impacts related with the extraction, processing, transport, maintenance, and disposal of building materials [33]. In this category, the requirements of *storage and collection of recyclables (prerequisite), construction demolition waste management planning (prerequisite), building life cycle impact reduction, building product disclosure and optimization sourcing of raw materials,* and *construction* and *demolition waste management* were fulfilled in the case study building. Accordingly, 10 out of 13 points can be earned.

4.6 Indoor environmental quality

The purpose of *Indoor Environmental Quality* is to enhance the surroundings of occupants by applying advanced design strategies and considering environmental factors such as air quality, lighting quality, and acoustic design that influence the way people learn, work, and live [33]. In this category, the requirements of *minimum indoor air quality performance (prerequisite), environmental tobacco smoke control (prerequisite), enhanced indoor air quality strategies, low-emitting materials,* and *interior lighting* were accomplished. Thus, 3 out of 16 points can be obtained.

4.7 Innovation

The purpose of *Innovation* is to accomplish considerable environmental performance by applying an innovative strategy which is not addressed in the LEED rating system [32]. For this purpose, a double glass photovoltaic module is placed on all windows on the southern facade of the case study building that allows to produce energy. Therefore, 5 points out of 6 points can be received.

4.8 Regional priority

The purpose of *Regional Priority* is to design the building considering its local environmental, social equity, and public health priorities [33]. Regional Priority credits are existing LEED credits. Within the scope of this category, 4 points can be gained from applying *surrounding density and diverse uses, bicycle facilities, rainwater management,* and *reduced parking footprint* in the case study building.

5 Results and discussion

Energy and water consumptions, and related expenses of the case study building (i.e., LEED building) and conventional building (i.e., non-LEED building) were calculated via MS Excel. The calculations were done assuming that a family of four lives in each apartment in the building. Two apartments exist in each floor of the building.

5.1 Water consumption cost

Figure 3 represents comparison results of water consumption for the LEED building (i.e., the case study building) and non-LEED building (i.e., conventional building). Figure 4 shows the break-even point for the cost of water-efficient systems utilized in the LEED building.
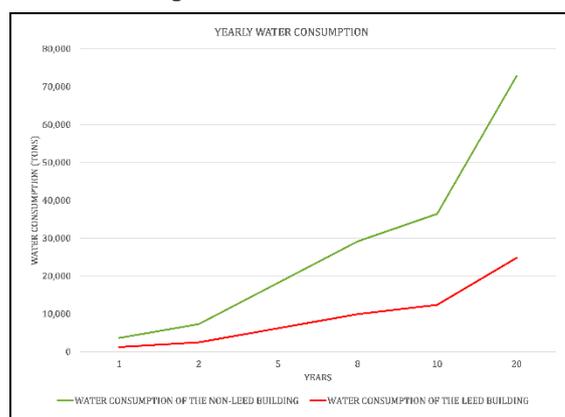

Figure 3. Comparing water consumption for LEED building and non-LEED building.

Figure 4. Break-even point for the cost of water-efficient systems utilized in the LEED building.

Water consumption may include humidification, irrigation, indoor plumbing fixtures and fittings, domestic hot water, boiler, reclaimed water, and process water used for dishwashers, clothes washers, pools, and relevant subsystems [33]. Table 1 demonstrates comparative analysis results of water consumption and related expenses for the LEED building and non-LEED building. In the non-LEED building, the peak value of water consumption is observed in July and this value is 322.18 tons, whereas the lowest value is detected in January as 288.87 tons. In the LEED building (i.e., case study building), the highest water consumption is monitored in August as 103.60 tons, while the lowest water consumption is calculated in January as 102.95 tons. It is estimated that one-year water consumption is 3,640.87 tons in the non-LEED building. The amount of one-year water consumption can decrease to

1,239.33 tons in the case study building by applying LEED v4.1 BD+C requirements. Accordingly, one-year water saving between the non-LEED building and LEED building is 2401.53 tons. On the other hand, water consumption expense for one-year in the non-LEED building is 18,932.50 TL. This value reduces to 6,444.54 TL in the case study building. In total, the amount of water saved at the end of a year is 12,487.96 TL. As a result, the amount of water consumption and related expenses for one-year decrease by 65.96% in the LEED building. If only additional water-efficient products/systems used in the LEED building are considered, the break-even point is 8 years and 2 months.

Table 1. Comparative analysis results for water consumption of LEED building and non-LEED building

Year	Non-LEED building		LEED building	
	Water consumption (Tons)	Cost (TL)	Water consumption (Tons)	Cost (TL)
0	0.00	95,545.00	0.00	197,503.00
1	3,640.87	114,477.50	1,239.33	203,947.54
2	7,281.73	133,410.00	2,478.67	210,392.07
3	10,922.60	152,342.50	3,718.00	216,836.61
4	14,563.46	171,275.01	4,957.34	223,281.15
5	18,204.33	190,207.51	6,196.67	229,725.68
6	21,845.19	209,140.01	7,436.00	236,170.22
7	25,486.06	228,072.51	8,675.34	242,614.76
8	29,126.93	247,005.01	9,914.67	249,059.29
9	32,767.79	265,937.51	11,154.01	255,503.83
10	36,408.66	284,870.01	12,393.34	261,948.37
11	40,049.52	303,802.52	13,632.67	268,392.90
12	43,690.39	322,735.02	14,872.01	274,837.44
13	47,331.25	341,667.52	16,111.34	281,281.98
14	50,972.12	360,600.02	17,350.68	287,726.51
15	54,612.99	379,532.52	18,590.01	294,171.05
16	58,253.85	398,465.02	19,829.34	300,615.59
17	61,894.72	417,397.53	21,068.68	307,060.12
18	65,535.58	436,330.03	22,308.03	313,504.66
19	69,176.45	455,262.53	23,547.35	319,949.20
20	72,817.31	474,195.03	24,786.68	326,393.73

5.2 Energy consumption cost

Figure 5 demonstrates comparison results of energy consumption in the non-LEED building (i.e., conventional building) and LEED building (i.e., case study building) as well as energy production in the LEED building. Energy consumption may include the usage of electricity, natural gas, chilled water, steam, fuel oil, propane, and biomass [33]. Figure 6 displays the break-even point for the cost of energy-efficient systems utilized in the LEED building. Table 2 shows comparative analysis results of energy consumption and related expenses for the non-LEED building and LEED building. In the non-LEED building, the energy consumption is 45,321.54 kw and it costs 32,178.29 TL for one-year. However, in the case study building, when the energy production from solar panels and solar windows are calculated, the remained energy after energy consumption at the end of the first year is 33,780.67 kw. This can provide a total of 19,254.98 TL as a profit for the owner and/or occupants. The comparison results of non-LEED building and LEED building show that total energy consumption difference is 7,9102.21 kw and cost difference is 51,433.28 TL at the end of the first year.
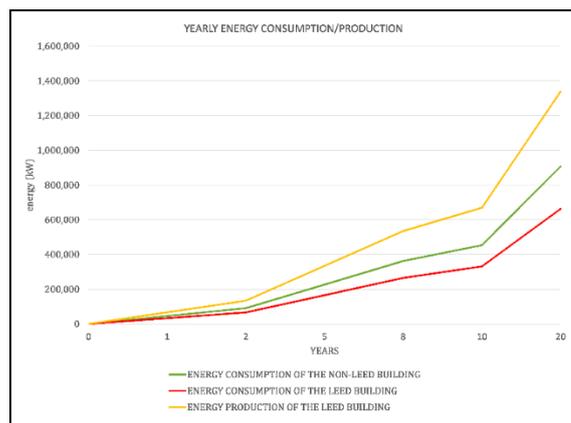

Figure 5. Comparing energy consumption for LEED building and non-LEED building.
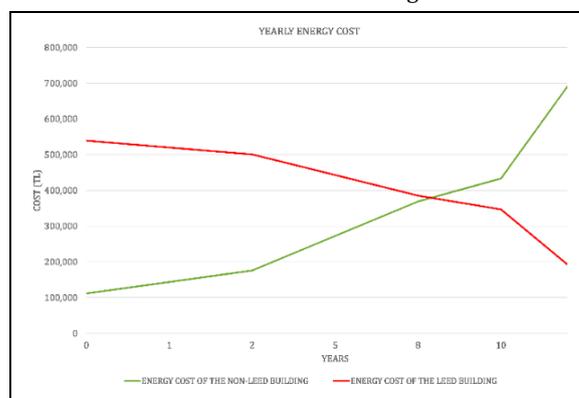

Figure 6. Break-even point for the cost of energy-efficient systems utilized in the LEED building.

Table 2. Comparative analysis results for energy consumption of LEED building and non-LEED building.

Year	Non-LEED building		LEED building	
	Energy consumption (KW)	Cost (TL)	Energy consumption (KW)	Cost (TL)
0	0.00	111,503.00	0.00	539,352.00
1	4,5321.54	143,681.29	-33,780.67	520,097.02
2	90,643.08	175,859.59	-67,561.34	500,842.04
3	135,964.62	208,037.88	-101,342.01	481,587.05
4	181,286.16	240,216.17	-135,122.68	461,332.07
5	226,607.70	272,394.47	-168,903.35	443,077.09
6	271,929.24	304,572.76	-202,684.02	423,822.11
7	317,250.78	336,751.05	-236,464.69	404,567.13
8	362,572.32	368,929.35	-270,245.36	385,312.14
9	407,893.86	401,107.64	-304,026.03	366,057.16
10	453,215.40	433,285.93	-337,806.70	346,802.18
11	498,536.94	465,464.23	-371,587.37	327,547.20
12	543,858.48	497,642.52	-405,368.04	308,292.22
13	589,180.02	529,820.81	-439,148.71	289,037.24
14	634,50156	561,999.11	-472,929.38	269,782.25
15	679,823.10	594,177.40	-506,710.05	250,527.27
16	725,144.64	626,355.69	-540,490.72	231,272.29
17	770,466.18	658,533.99	-574,271.39	212,017.31
18	815,787.72	690,712.28	-608,052.06	192,762.33
19	861,109.26	722,890.57	-641,832.73	173,507.34
20	906,430.80	755,068.87	-675,613.40	154,252.36

Accordingly, the amount of energy consumption and related expenses for one-year decrease by 59% in the LEED building. If only additional energy-efficient products/systems utilized in the case study building (i.e., LEED building) are considered, the break-even point is 8 years and 3 months. If MEP drawings are included within the scope of the case study, energy consumption in the LEED building would decrease much more than 59%. Accordingly, the break-even point for the cost of the energy-efficient systems would be much earlier than 8 years and 3 months. Consequently, more LEED criteria would be fulfilled in the case study building that could result in higher points in the LEED v4.1 BD+C certification system.

5.3 Total project cost

Figure 7 shows the break-even point for the additional total cost of the LEED building. Table 3 represents comparative analysis results for the total project cost of the non-LEED building and the LEED building.
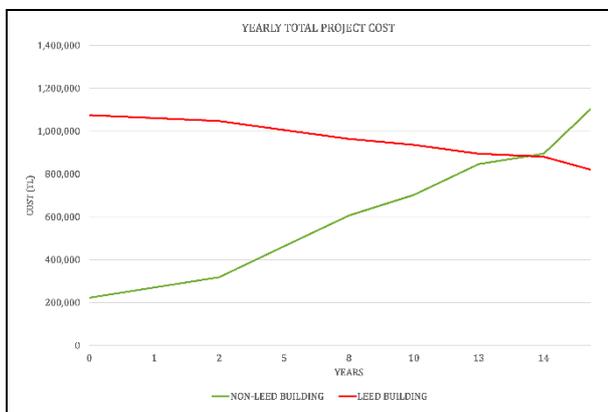

Figure 7. Break-even point for the additional total cost of the LEED building.

Table 3. Comparative analysis results for the total project cost of the LEED building and non-LEED building.

Year	Non-LEED building Cost (TL)	LEED building Cost (TL)
0	222,702.40	1,074,833.04
1	270,682.03	1,060,964.44
2	318,661.67	1,047,095.84
3	366,641.30	1,033,227.24
4	414,620.93	1,019,358.64
5	462,600.57	1,005,490.05
6	510,580.20	991,621.45
7	558,559.83	977,752.85
8	606,539.47	963,884.25
9	654,519.10	950,015.65
10	702,498.73	936,147.05
11	750,478.37	922,278.45
12	798,458.00	908,409.85
13	846,437.63	894,541.25
14	894,417.27	880,672.66
15	942,396.90	866,804.06
16	990,376.53	852,935.46
17	1,038,356.17	839,066.86
18	1,086,335.80	825,198.26
19	1,134,315.43	811,329.66
20	1,182,295.06	797,461.06

Additional total cost of the case study building was calculated considering the LEED related expenses which cover the cost of sustainable materials as well as energy-efficient and water-efficient technological products/systems such as rainwater storage system, grey water recycling system, solar panels, solar windows, motion sensor lighting, air sensors, water-efficient fixtures, electric car charger, and carbon neutral products (e.g., interior and exterior coverings).

Results show that an important difference between the initial cost of non-LEED building and LEED building (i.e., case study building) exists. In this study, the initial cost of the building does not cover the rough works (e.g., excavation, structural construction works); on the contrary, cover the finishing works (e.g., coatings) and innovative applications for increasing building water and energy efficiency (e.g., solar panels). The reason of this is that initial cost of rough construction cost for a similar type and dimension building hardly changes to a large extent. Moreover, the significant cost difference usually arises from the finishing works and innovative applications. This fact was proved by the outputs of the case study (i.e., LEED building). The initial cost of the non-LEED building is 222,702.40 TL TL while the initial cost of the LEED building is 1,074,833.04 TL. The reason of initial cost increase in the LEED building is the additional cost of sustainable materials and advanced technological products which are required for the fulfillment of the LEED procedure. However, if energy and water consumptions are compared, the case study building is much more energy, water, and cost efficient than non-LEED building in the long run. According to the break-even point for the LEED expenses (i.e., additional total cost), including the cost of sustainable materials and technological products, the profit will be deriven after 13 years 8 months and 12 days.

6 Conclusions

This study shows (1) a sustainable high-rise residential building design using LEED v4.1 BD+C and BIM, and (2) the discrepancies in energy and water consumptions, and total project cost between the LEED building and non-LEED building. Within this scope, the additional cost related to water and energy efficient systems and the additional total cost for the LEED building were analyzed to calculate the respective break-even points. A literature review and a case study were conducted for achieving the research objective. Results make a significant contribution to the AEC literature and industry by displaying the requirements and design process of a high-rise residential building using LEED and BIM. This study adds original value to the literature and industry by ensuring practitioners and researchers with constructive information about the energy, water, and cost performance of LEED buildings. Findings would be useful for the practitioners and researchers in the AEC industry. Further, results provide an insight to the AEC professionals about the value of green buildings.

The practices adopted in this case study ensure to fulfill the sustainability requirements of LEED v4.1 BD+C for a high-rise residential building. The case study building (i.e., LEED building) can achieve 31 credits and 9 prerequisites which allows to obtain 61 points and LEED Gold certificate. Results of the case study show that a significant reduction in the water and energy consumption cost is observed in the LEED building. By applying LEED v4.1 BD+C procedures, water consumption of the building is reduced by 65.96%, and energy consumption of the building is reduced by 59%. The initial cost of the LEED

building is 1,074,833.04 TL which is 852,230.64 TL higher than the non-LEED building. The reason of increase in the initial cost of the LEED building is the use of additional sustainable materials, water and energy efficient products/systems, and innovative technologies in the building design. As a result, the break-even point for the additional total cost of the LEED building is 13 years 8 months and 12 days.

One of the limitations of this study is to develop the 3D model based on the 2D structural and architectural drawings without using MEP drawings. The other limitations are not performing building energy analysis and not considering life-cycle assessments (LCAs) for the building materials. If the MEP drawings, energy analysis, and LCAs are performed, it is crystal clear that the case study building would be more environmentally sustainable, energy-efficient, and value-added in the long run. Furthermore, these practices would ensure the achievement of higher points in the LEED v4.1 BD+C, and accordingly higher level of green building certificate for the case study building.

One of the future directions of this research would be to compare a large number of non-LEED and LEED buildings in order to generalize the results. The other future work could be to include energy analysis for the building and life-cycle assessments for the building materials within the scope of the research. Another future step would be to address different types of buildings such as hospital, school, office building, manufacturing plant, and shopping center, and other LEED rating systems such as LEED Building Operations+Maintenance and LEED Zero.

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8 Author contribution statements

Senem SEYIS contribute to creating the idea, performing the literature review, identifying and managing the concept and design process of the research, supplying the materials used, examining the results, assessing obtained results, preparing the manuscript, conducting critical analysis of the intellectual content, final approval, and full responsibility.

9 Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared.

There is no conflict of interest with any person / institution in the article prepared.

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