BIM-BASED ENERGY PERFORMANCE EVALUATION OF A BUILDING ENVELOPE IN SEMI-ARID CLIMATE ZONE IN THE MIDDLE EAST

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ABSTRACT

The BIM building envelope integrates a BIM building's internal and external environments, improving energy efficiency and substantially lowering energy usage. This research aimed to assess the energy efficiency of typical building envelope materials in Iran. To do this, we used Autodesk Revit® to generate a generic model and DesignBuilder® to conduct an energy analysis. The BIM building envelope integrates a BIM building's internal and external environments, improving energy efficiency.

A BIM building envelope energy analysis was performed on 58 local wall constructions material in Iran. Then, the energy consumption of a BIM building's HVAC system was then compared against the costs of all external wall alternatives to determine the optimal layer combination. Consequently, the energy simulation results demonstrated that the double external wall structure, 2AAC block core, with XPS (CFC) insulation exterior wall and the single external wall, PERLEX Ultra-Lightweight (PUW) wall performed better. In addition, the clay block wall is found to be the optimum solution for the case study location. The applicability of the proposed system is validated with a case study of a traditional residential building.

KEYWORDS

Sustainable Design, Environmental Considerations, Energy Efficiency, Building Information Modeling, BIM

1. INTRODUCTION

This study examines Building Information Modeling (BIM) from an international perspective. It shows how current building practices in residential and industrial sectors have created environmental pollution and have lost energy efficiency due to global warming. Fortunately, these harmful trends have been mitigated by a growing demand for green buildings and sustainable energy (Holmberg, Siilasto, Laittinen, Andersson, & Jasberg, 2013). A sustainable energy system for managing energy supply and demand will help alleviate the problems caused by

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global climate change (Solomon & Krishna, 2011). Population growth has been a significant challenge for the energy sector as it strives to meet building needs and introduce energy-saving criteria (See, et al., 2011).

According to the International Energy Agency (IEA) and the Energy Information Administration, the residential sector is responsible for more than 30% of the total final energy consumption in the world and the following 20 years (International Energy Agency (IEA), 2017; U. Energy Information Administration, 2019). Also, based on this agency, electricity would be the largest energy source used as the basis for lighting, cooling, and appliances in the building between 2015 and 2040 (International Energy Agency (IEA), 2017). From the CO_2 emission point of view, buildings are responsible for about 30% of CO_2 emissions (Delavar & Sahebi, 2020).

The Iran Energy Balance Sheet states that the dwelling, commercial, and public sectors comprise more than 40% of all energy consumption. The dwelling, commercial, and public portion is over 47% of the country's electricity consumption (Ministry of Electricity and Energy of Iran, 2017) Also, dwelling sectors have been the most significant contributors to pollution production. The buildings allocate about 26.4% of their carbon dioxide emission (Ehyaei, 2020). Therefore, buildings are considered a key component of sustainable development and societal benefits. They can also harm the environment regarding energy consumption and greenhouse gas production. Thus, the negative building impacts on environmental concerns have given the construction industry a great interest in applying sustainable strategies and measures to enhance building energy performance through efficient ways (Stevanović, 2013).

Meanwhile, in residential buildings, Noori and Hwaish (2015) reported that building envelopes allocate more than 50% of the business sector's embodied energy. This refers to the building's life cycle cost from manufacturing materials used in construction to recycling materials and restoration at the end of the building's life (Thorpe, 2015) Moreover, the building envelope also contributes to approximately 50% of the building's total heat gain (Noori, 2015; Gratia & Herde, 2007). In this regard, building envelopes are the critical path for thermal energy transfer between internal and external built environments. Thus, buildings must maintain a constant, comfortable, and adequate indoor climate in parallel with managing energy usage more sustainably based on a changeable external climate environment. To achieve this objective, efficient building envelopes are required (Földváry, Pustayová Bukovianska, & Dušan, 2015).

Building Information modeling (BIM) analyzes building performance and has been applied in the design and construction industry from various aspects (Čuš Babič, Podbreznik, & Rebolj, 2010; Suermann & Issa, 2009; Popov, Juocevicius, Migilinskas, Ustinovichius, & Mikalauskas, 2010; Welle, Haymaker, & Rogers, 2011; Jung & J., 2011; Zhang, Teizer, Lee, Eastman, & Venugopal, 2013; Santos, Costa, Silvestre, & Pyl, 2019). BIM-based modeling and building performance analysis, presented together as an integrated framework, provide the platform for efficiently empowering construction quality. Besides, several studies have been done on energy optimization, but the new emphasis on improving building energy performance through applying BIM on sustainable construction strategies has received much attention (Kumar, 2008; See, et al., 2011). As social, economic, and environmental sustainability are the significant basis of sustainable building design, sustainability simulation design can be effectively carried out through BIM utilization in the early stage of design. On the other hand, the sustainability criteria, including building material and energy consumption aspects, can be accomplished through BIM tools development (Chong, Lee, & Xiangyu, 2017).

The building envelope is one of the most important factors in determining how much energy a building consumes, and it has a direct impact on design and performance. Selecting building materials efficiently can assist the designer in creating a sustainable building design. The thermal properties of building envelope (BE) systems can considerably impact a 'building's total energy performance; hence, they must be accurately determined. This research presented a practical pattern for efficient external wall layers (including isolations, structure, and interior and exterior finishes). As a result, this research can significantly increase building energy efficiency while investigating construction methods and commonly used materials in Iran and similar construction industries worldwide.

BIM is an integrated workflow that facilitates the interchange of multidisciplinary building information by providing interoperability across design stakeholders (Eastman, Teicholz, Rafael, & Liston, 2008; E. Macii, 2011). Building performance evaluation via analysis software is now done largely after the design stage, and hence is not part of the design decision-making process. Building performance assessment should be smoothly integrated into the design process to properly analyze many performance parameters of the building design, such as envelope material, shape, and energy efficiency (Schlueter & Thesseling, (2009)).

The BIM tool is specifically developed to enable energy analysis applications to identify the structure's potential gain or loss of energy and detect and estimate its sustainability early in the conceptual design process. As a result, the owner and project team will analyze sustainability from the start of the project's execution. BIM is a great application for sustainable design because of its capacity to test and analyze repeatedly and enhance design (A Ebrahim, 2019). On the other hand, incorporating a BIM-based performance design assistance into the design process is becoming more common, allowing designers to quickly select the best design solutions for their projects (Natephra, Yabuki, & Fukuda, 2018).

Acoustic analysis, carbon emission, construction, and demolition waste management, daylighting analysis, operational energy consumption, and water usage, building orientation, building form analysis, are all examples of how BIM and BIM-based applications can help with sustainable design and green building practices (Cavalliere, Habert, Dell'Osso, & Hollberg, 2019; Ansah, 2019). BIM-based building energy analysis is gaining popularity because it expedites the traditional modeling and simulation process by providing easy and rich access to building information, saving significant time and effort for energy modelers (US General Services Administration (GSA), 2012; Gerrish T. R., 2017).

Several research efforts on data interchange between BIM and energy simulation systems have been made. The majority of suggested data exchange techniques fall into three categories. First, API-based data exchange must be built using specialized BIM technology, such as Revit or ArchiCAD. Energy simulation may then be utilized by external simulation tools and a directly connected application programming interface (API).

Kim et al. (2015) created a Modelica-BIM library to facilitate BIM-based energy simulation by semi-automatically translating BIM models to building energy models using the Revit API. This method can considerably decrease data loss between two different tools during model translation. The biggest disadvantage is the lack of flexibility and extension, as BIM design data may only be communicated via the API of a connected BIM authoring tool.

Second, this method uses gbXML-enabled data exchange as a bridge to move building design information from BIM tools to energy simulation tools. GbXML is supported by some top BIM suppliers, including Autodesk, Trimble, Graphisoft, and Bentley, and has evolved into a de facto industry standard template for facilitating interoperability across diverse BIM design and energy simulation products (gbXML, 2020). Thermal parameters like thermal conductivity and specific heat may also be sent using the gbXML-based file (Pinheiro S., et al., 2018). Ham and Golparvar-Fard (2015) created a gbXML-based BIM for trustworthy building energy performance modeling by mapping real thermal values to building elements. Guzman and Zhu (2014) created a gbXML-based file converter to simplify information interchange on building design and energy analyses. Garwood et al. (2018) developed a novel approach for generating gbXML building geometry from a point cloud model for accurate and efficient building energy modeling. Through a small-scale building project, Abanda and Byers (2016) demonstrated the capability of utilizing gbXML to translate BIM information to energy simulation tools. Because the gbXML standard employs centreline geometry, this approach always results in computed surface area and space volume variations. This sort of discrepancy may surpass the typical engineering tolerance for big complex building geometries, resulting in an overestimation of building energy usage (Pinheiro S., et al., 2018). Another major disadvantage of the gbXML format is the absence of geometric depiction of heating, ventilation, and air conditioning equipment and systems (Extending the information delivery manual approach to identify information requirements for performance analysis of HVAC systems, 2013).

Finally, IFC-enabled data exchange is an object-oriented neutral data model established by buildingSMART to describe, communicate, and share information throughout the whole building lifecycle. IFC is now an international data standard supported by practically all BIM tools. Model View Definitions (MVD), a subset of IFC that focuses on satisfying a specific exchange scenario such as energy simulation or structure analysis, was designed to improve data flow across applications. Based on the IFC 2 3 3, the Coordination View is the first and most common MVD. BuildingSMART released two more MVDs based on the IFC4.1 standard in 2015: Reference View and Design Transfer View. A variety of customized MVDs have been developed to enhance data transmission between BIM and energy simulation programs since the development of the MVD standard (Pinheiro S., Wimmer, Maile, & O'Donnell, 2016). For energy modeling, Andriamonjy et al. (2018) created an MVD that may be utilized with the Modelica language. Using IFC-based mapping tools, Kim and colleagues (Kim & Yu, 2016a; Kim K. a., 2016b) have created an energy analysis model for buildings that incorporates material attributes.

This study investigates the interoperability of the BIM model, and the energy simulation tool facilitates modeling and building operation analysis; additionally, BIM-based energy simulation results are validated and compared with data from the actual annual energy consumption of a residential building. Various possible wall combinations are investigated to achieve the building envelope energy efficiency. Because Autodesk Revit and DesignBuilder are widely used tools for BIM authoring and energy simulation, these application tools were chosen for the BIM-based energy simulation in this study. The DesignBuilder software is specialized in building energy simulation based on evaluating thermal comfort and solar gain through windows. (Chowdhury, Rasul, & Khan, 2008); whereas, this study aims to provide a BIM-based strategy that can be used to assess green building performance and identify appropriate measures that can greatly improve building performance.

The rest of this paper is organized as follows: Section 2 reviews previous studies. Section 3 provides the methodology of modeling and energy analysis by applying BIM. Section 4 discusses the simulation results, and section 5 presents the optimization based on the analysis outcome and material costs. Finally, section 6 concludes this research by mentioning the limitations and future research suggestions.

2. LITERATURE REVIEW

Generally, the scope of current construction projects has been expanded and is challenging to manage. By improving technology advancements, most construction companies are trying to apply innovative technologies in their project to facilitate their process (Alshawi & Ingirige, 2003; Chan, Scott, & Chan, 2004). As one of the computer-based tools, BIM has a high quality of collaboration and coordination through various project phases from the conceptual study to the design stage to construction (Shafiq, Matthews, & Lockley, 2013; Eastman, Teicholz, & Sacks, BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors, 2011). The client can clearly understand the project's needs, budgets, and planning by applying BIM. Simultaneously, the designer can design and store information, such as building material characteristics and analyses. The contractor can adequately manage the construction phases more efficiently (Grilo & Jardim-Goncalves, 2010; Azhar, J., & R., 2011; Kota, Haberl, J.Clayton, & Yan, 2014). BIM can share information with standard software tools as a comprehensive database of integrated information. It can be applied as the central model to obtain precise geometry modeling and building performance evaluations in various fields, including architectural, structural, MEP, energy performance, acoustic, and lighting. BIM can also play a significant role in reducing project time and costs (Ahn, Kim, Park, Kim, & Lee., 2014; Park, Park, Kim, & Kim, 2012; Lei & Weifang, 2012; Biagini, Capone, Donato, & Facchini, 2016; Cao, et al., 2015; Nguyen, Toroghi, & Jacobs, 2016; See, et al., 2011).

Besides, according to recent worldwide environmental crises that view energy consumption as a critical and sometimes threatening factor, the necessity of an approach to clean energy resources and sustainable development should be considered. Built environments have increasingly affected environmental quality, and buildings consume many energy resources during construction (Bynum, Issa, & Olbina, 2013). The building design process has recently been deeply affected by increasing global environmental concerns, which must be addressed in building energy simulation tools (Malkawi, 2004). The most critical environmental concerns pursue the construction industry (specifically designers) to bring significant attention to building energy performance. This can happen through assessing design alternatives associated with improving building energy efficiency without air pollution, power outages, or building envelope energy loss in the early phases of project planning (Bynum, Issa, & Olbina, 2013; Lin & Gerber, 2014).

The building envelope shields the interior and occupants from the effects of the environment and its microclimate. The envelope characteristics influence a building's visual and thermal comfort and energy consumption (Iwaro & Mwasha, 2013). The airtightness of a conditioned building's envelope determines its heating or cooling load (Chen, Yang, & Zhang, 2018).

Sustainable buildings are expected to have high thermal efficiency during a building's life span (Pulselli, Simoncini, & Marchettini, 2009). Sustainably designed buildings use approximately 70 to 80% less energy than existing conventionally designed buildings (Khudhair & Farid, 2004). Shadram (2018) examined the embodied energy of building materials with operational energy to propose optimal design strategies. This research was conducted on a dwelling in Sweden, and results showed that initial design solutions are crucial steps in reducing operational building energy. Related studies assessing building energy performance confirmed the significant effect of building envelopes on thermal comfort by lowering heating and cooling loads due to the building envelopes' thermal energy exchange between internal and external environments. Improving thermal insulation material has resulted in energy savings and sustainable buildings (Meester, Marique, Herde, & Reiter, 2013; Egwunatum, Joseph-Akwara, &

Akaigwe, 2016; Noori, 2015). Yousefi (2017) conducted a study evaluating occupants' behavior based on the building envelope efficiency in different climate zones. The number of heating degree days (HDD), Cooling degree days (CDD), average temperature, and precipitation are the contributors in defining climate zones (Baechler MC, 2010). The climate in the United States can be defined as tropical in Hawaii and Florida, arctic in Alaska and semi-arid in the great plains west of the Mississippi River, and arid in the Great Basin of the southwest (Climate Information, 2019).

There are four key parameters connected to building envelope design, in addition to external influences (e.g., climate) that will impact the building's thermal performance and energy efficiency. External wall insulation thickness, roof heat transfer coefficient, solar heat gain coefficient of the external window, and window-to-wall ratio (WWR) are among them (Li, Zhang, Zhang, & Wu, 2021). As a result, selecting the right materials and design features for the building envelope can help reduce cooling and heating loads. This is due to the building envelope's sensitivity to the weather, which is a major determinant of the energy required to maintain building inside thermal comfort (Noori, 2015). Green retrofitting existing buildings, on the other hand, presents numerous obstacles, including selecting appropriate retrofit methods and effectively lowering energy consumption, as well as life cycle cost analysis and the return-on-investment period (Ma, Cooper, Daly, & Ledo, 2012; Sanhudo, et al., 2018).

Sadineni and Suresh (2011) conducted a comprehensive review of the building envelope components and improvements in building energy efficiency. They focused on comparing the effects of different wall types, including Trombe walls, ventilated walls, and glazed walls. Friess and Rakhshan (2012) evaluated the impact of using a mid-plane insulated prefabricated block to obtain maximum U value and the effect on energy consumption when using a thermal bridge on a reinforced concrete frame. They also found that using proper external wall insulation measures alone can achieve up to 30% energy savings. Otavio (2012) recommended applying thermal insulation materials for an energy-efficient building. Balaras et al. (2005) audited 193 European buildings to determine buildings' heating energy consumption by considering the effective energy consumption parameters based on envelope insulation materials, age, and heating system conditions. Their results revealed that five European countries' residential buildings' annual heating energy consumption exceeded the European average by approximately 38%. Xinzhi Gong (2012) assessed seven residential buildings to minimize energy consumption by applying the orthogonal approach. The thickness of insulation and the sunroom depth is defined as effective parameters on the annual energy consumption.

Furthermore, De Meester et al. (2013) demonstrated that improving building insulation yields greater energy savings for heating than simply human behavior. Snell (2017) conducted a comparison on the two different concrete mixes, including Portland cement (PC) and geopolymer cement concrete (GCC) mixes. Thermal conductivity, heat capacity, and compressive strength are considered primary evaluation parameters in this application. Song (2018) investigated optimizing the building envelope and equipment using phase change materials through a comprehensive review.

In recent years, the most remarkable studies have been done on building energy optimization (Boeck, Verbeke, Audenaert, & Mesmaeker, 2013), but few of them have considered the BIM-based building performance optimization (Lin & Gerber., 2014; Welle, Haymaker, & Rogers, 2011). In the design phase, BIM has a robust capability that helps users achieve a more efficient building. Energy analysis is often complicated and costly. It can also be delayed right up to the end of the design process (Moakher & Pimplikar, 2012). BIM makes it possible to import multidisciplinary information into a model and consolidate it with other disciplines. Integrated and interconnected BIM modeling knowledge can make energy simulation more efficient in the early design stage. The data created from simulation can be used for various design alternatives (Newton & Tucker, 2009). Farzaneh (2018) developed a BIM-based framework to create the building energy model (BEM) system for the design process. The work/flow data and BIM preprocessing are investigated to help the user better understand information flow. Gerrisha et al. (2017) presented practical guidelines for managing data to support building performance management. They interviewed designers and operators in which BIM capabilities in building performance analysis were investigated. Bank (2014) investigated the integration of BIM and a decision-making model to select optimum sustainable building materials by focusing on LEED system criteria, which resulted in a BIM model focusing on the thickness of walls and floors. Rahmani (2015) integrated the BIM-based framework to optimize various design alternatives used to evaluate environmental issues and their effect on energy consumption. Abanda and Byers (2016) found that building orientation can affect building energy consumption. In this regard, they used BIM capabilities as a powerful solution. Kota (2014) presented an integrated framework based on BIM and daylight analysis tools, enabling each component and material to benefit from lighting. One aspect of employing BIM is to reduce the carbon footprint associated with CO_2 emissions from power plants. Iddon and Frith (2013) used a BIM tool to estimate the stored carbon and produced carbon for four rooms representing various building methods during the building life span. The results showed that approximately 70% of produced carbon originates from the electrical energy needed to heat a house. Thus, selecting an efficient building envelope can minimize the carbon footprint by applying BIM to evaluate the embodied carbon of building elements and suggest more sustainable heating options based on the BIM analysis. Besides, many researchers measure building orientation and positioning based on daylight analysis through natural heat gain and their impacts on energy consumption by applying BIM and energy simulation (Garcia & Zhu, 2015; Moakher & Pimplikar, 2012; Azhar, J., & R., 2011). Habibi (2017) proposed BIM-based improvement strategies to achieve energy efficiency buildings by showing that the natural environment and passive design strategies play a significant role in minimizing building energy consumption. Amini (2018) developed a framework to select the best building design based on the sustainability and resiliency criteria when the design parameters are uncertain through applying the multiple attribute decision-making (MADM) method. In the same year, Francisco (2018) presented an eco-feedback system to assess the effect of occupants' behaviors on reducing building energy consumption by using a BIM model to compare energy consumption values. Akbarnezhad et al. (Akbarnezhad, Ong, & Chandra, 2014) developed a sustainable deconstruction technique that relied on BIM information to recover energy and cash invested in building components. Stegnar and Cerovsek (2019) presented a hybrid solution based on BIM and other information technologies to support energy rehabilitation activities such as energy usage diagnosis and retrofitting decision-making. Their research gave little attention to integrating BIM with green building evaluation and failed to highlight the strategies that may be taken to improve green building performance.

Valinejad (2015) estimated operational energy consumption based on the combination of windows, walls, and floor types by applying BIM in a two-story bungalow house in Johor, Malaysia. Natephra et al. (2018) proposed a framework to assess a building's overall thermal transfer value (OTTV) through BIM's thermal properties. Hong (2020) applied the life cycle assessment (LCA) and life cycle cost analysis (LCCA) to evaluate the total life cycle energy

(LCE) and life cycle cost (LCC) of the passive house-inspired building envelopes in the United States. In this study, the LCA was conducted based on the ISO 14040/14044. Results indicated that double-stud walls were identified as the most effective system in terms of economic and environmental aspects in all the climate zones.

The researchers' findings disclosed that the most significant issues relating to building energy consumption are the energy parameters. The building envelope has a vital role in energy efficiency with its crucial energy-saving elements, but its importance is not always applied in new construction. Research efforts based on shape and types of envelope material have yielded many options, which are not being utilized as frequently as needed.

Based on the previous studies mentioned above, it is revealed that building envelop is the most influential parameter in building energy consumption by contributing approximately 50% of the building total heat gain. Further, most research works have demonstrated energy performance through energy analysis packages but only considered a few comparisons between building elements such as windows, walls, and floors. This literature review shows a research gap for explicit research on the building envelope, including wall thickness, insulation type, properties, and wall execution method. This research aims to develop a practical, sustainable pattern design for building envelopes with material properties and performance considerations to evaluate building energy consumption through BIM utilization. In this research, the authors proposed a sustainable external wall design pattern based on the different wall structure alternatives and optimized the outcome for different objectives (i.e., annual energy consumption and material cost).

3. RESEARCH METHODOLOGY

This paper presents an energy value analysis of BIM and its role in improving problems using traditional energy-saving building envelope material. To validate the outputs of this research, a real case study is utilized. The focus is on building envelope materials. Different types of external wall structures with different insulation materials are modeled, and the data is saved for energy simulation analysis. In the end, optimization is proposed to help designers select the most efficient material and wall structures for building envelopes. Critical assumptions are defined based on standard practices in Iran's construction industry during modeling.

3.1 Generic Plan

Before starting modeling with Autodesk Revit® (Autodesk Inc., 2019) software, we investigated a common floor plan based on Iran's various climate conditions. A 3D model was then developed based on one plan selected to represent a generic floor plan suitable for Iran's most common climate characteristics. The desired generic building model is located in the Tehran province of Iran.

Iran contains six climate zones: Arid desert hot, Arid desert cold, Semi-Arid desert hot, Semi-Arid desert cold, Mediterranean hot, and hot summer continental. Teheran is located at 35°40'N, 51°19'E, 1191m (3907 ft.) with around 8.4 million in the city and 14 million in the wider metropolitan area. It has a semi-arid climate, and the average monthly temperatures differ by 28.3 °C (82.94 °F).

Figure 1 shows Tehran's maximum (hottest) temperatures in July and the minimum (coolest) temperature in January. The average temperature for the whole year is presented in Table 1.

The specifications of a generic model are described in Table 2.

FIGURE 1. Tehran climate graph (Tehran Climate, 2019).

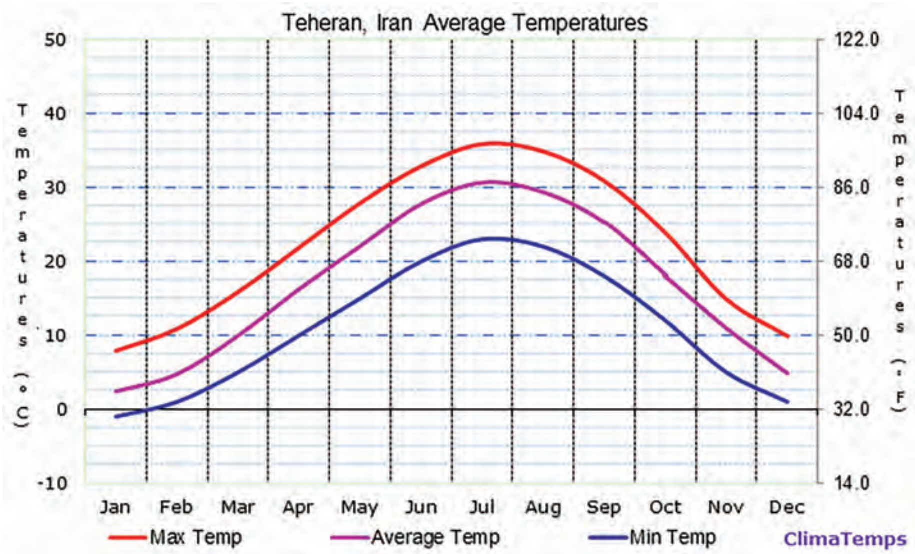


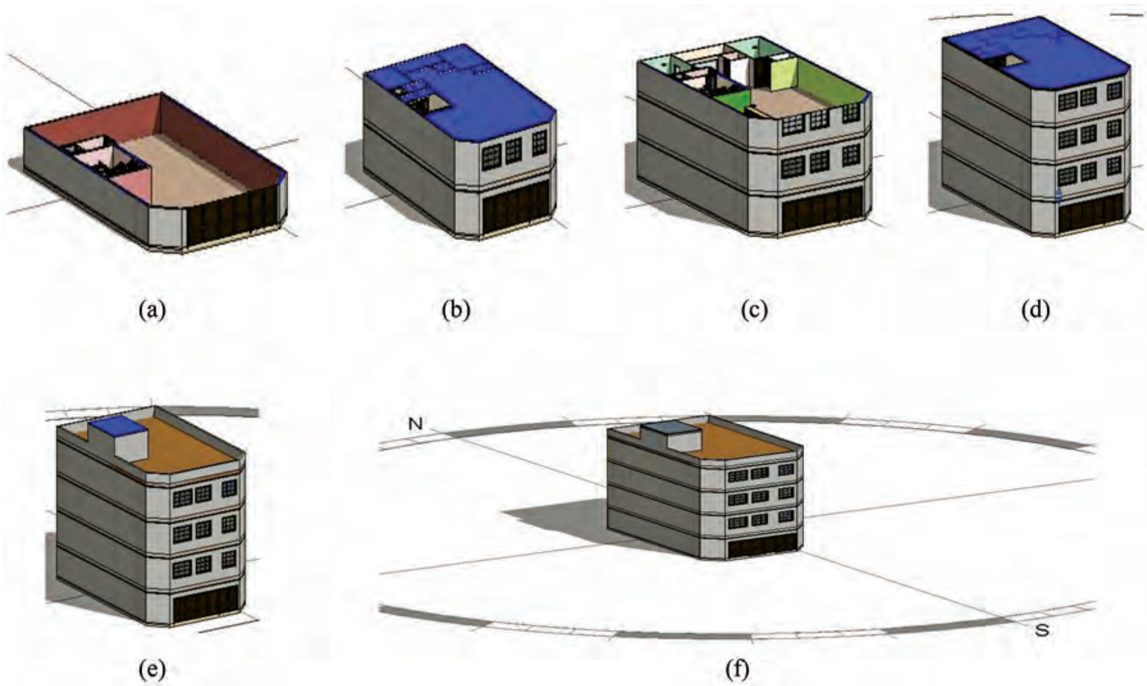
TABLE 1. Average temperature table for Tehran, Iran (Tehran Climate, 2019).

Temperature °C (°F)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max Temperature	8 (46.4)	11 (51.8)	16 (60.8)	22 (71.6)	28 (82.4)	33 (91.4)	36 (96.8)	35 (95)	31 (87.8)	24 (75.2)	15 (59)	10 (50)	22.4 (72.4)
Average Temperature	2.5 (36.5)	4.9 (40.8)	10.1 (50.2)	16.4 (61.5)	22.2 (72)	27.9 (82.2)	30.8 (87.4)	29.5 (85.1)	25.4 (77.7)	18.2 (64.4)	11.1 (52)	5 (41)	17 (62.6)
Average Min Temperature	–1 (30.2)	1 (33.8)	5 (41)	10 (50)	15 (59)	20 (68)	23 (73.4)	22 (71.6)	18 (64.4)	12 (53.6)	5 (41)	1 (33.8)	10.9 (51.7)

TABLE 2. General project specifications.

General Project Specifications	
Location	Tehran
Built-up Area	873.68 m^3
Number of floors	4
Main Construction	Steel Structure
External walls	Various
Roof system	Block Joist

FIGURE 2. Modeling of the generic building in Revit® (Autodesk Inc., 2019)



3.2 Modeling Process

As one of the well-known existing modeling applications, Autodesk Revit provides the possibility of structural, architectural, and MEP[3] modeling in an integrated model. This software provides an appropriate environment for engineers to model a project with different levels of detail, thereby creating integration in all phases of a construction project. Figure 2 presents Revit's modeling process, showing a 3D view of the generic model (a–e) and its orientation (f).

The first floor consists of parking and stair areas. The 2nd, 3rd, and 4th floors consist of apartments (including bedrooms, bathrooms, restrooms, stairs, and living room). The structural and architectural models are produced in Revit software. It is essential to consider the shapes and dimensions of elements to realize a model accurately. The BIM model must be imported into DesignBuilder software (DesignBuilder Software ltd, 2019) to analyze energy. As an energy simulation software, DesignBuilder uses the EnergyPlus™ engine for analysis (Chowdhury, Rasul, & Khan, 2008). HVAC components' energy consumption and solar shading were obtained by calculating heating and cooling consumption as the output performance data in DesignBuilder (DesignBuilder Software ltd, 2019). The defined room areas of a floor in Revit® (Autodesk Inc., 2019) were used in a saved gbXML file, as presented in Figure 3. Other detailed information related to room areas is shown in Appendix 1.

The building data is transferred through the Green Building eXtensible Markup Language (gbXML) (Schema, Inc, 2019) analysis software. Figure 4 represents a created gbXML file. There are two ways to transfer a BIM model from Revit to DesignBuilder: One is to use the DesignBuilder Revit plugin available as an add-in of Revit software, and the other is to use the

3. Mechanical, Electrical and Plumbing

FIGURE 3. Defining room area to plan.

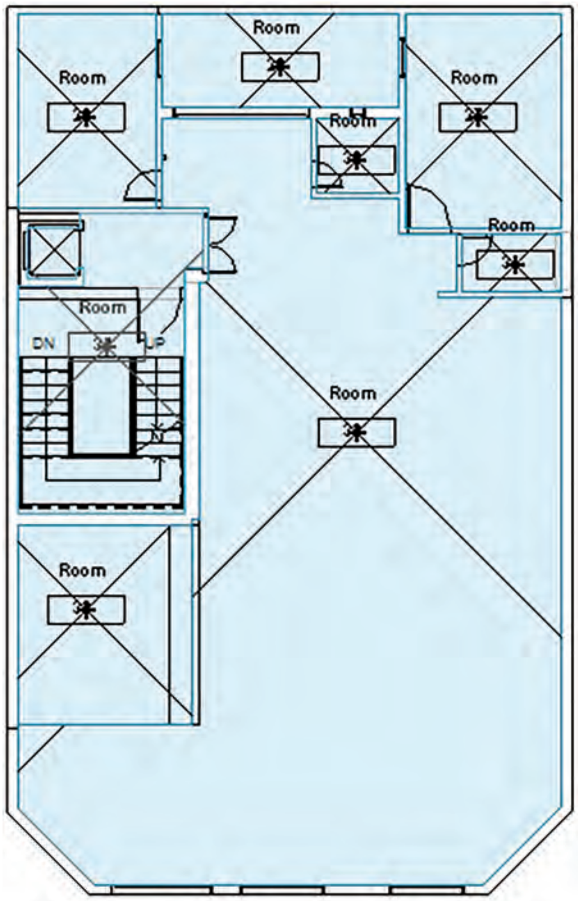


FIGURE 4. Exporting gbXML data file as an analytical model.

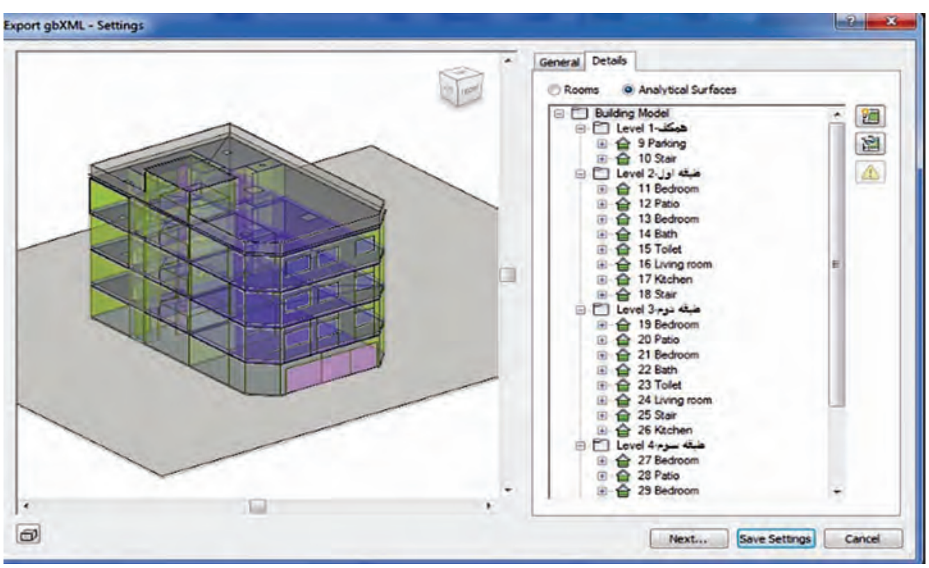
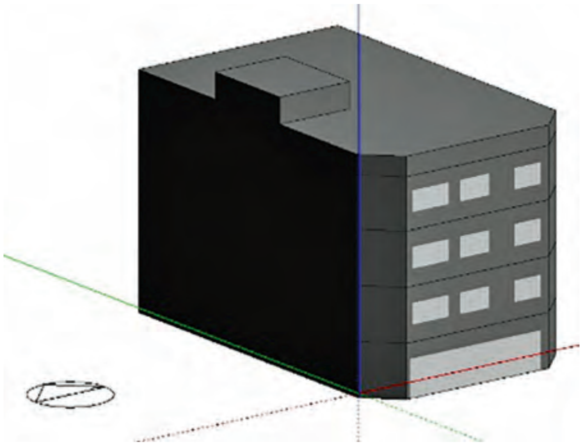


FIGURE 5. Model geometry layout in (DesignBuilder Software ltd, 2019).



gbXML data file method. The second approach was selected to transfer the generic model data into the energy analysis software in this research.

3.3 Energy Analysis in DesignBuilder Software

The generated model is imported into DesignBuilder software by the gbXML data file in the first step. Figure 5 presents the imported model in DesignBuilder. Note that generally, an energy analysis software package has the capabilities of a 3D interface for modeling, but these capabilities have low graphical quality.

Iran's Ministry of Housing and Urban Development (2010) classifies building based on three principles found in the National Building Regulations on Efficient Energy Use, Addendum 19:

I. The continual day and night use of a building during a year;
II. The severity of probable temperature differences between the exterior and interior of a building;
III. The importance of stabilizing the building's indoor temperature;

3.3.1 Design Parameters in Design Builder Software

To analyze the generated model's energy usage, the design parameters must be defined in primary design steps in the DesignBuilder software. Significant effective parameters are mentioned here that should be defined before simulation. Some of those factors are considered based on Iran's building characteristics, and others are selected as software defaults.

Non-construction parameters

The activity as a first design parameter includes an Activity Template, Occupancy, Metabolic, etc. The activity of each zone must be determined to ensure accuracy. For instance, the bedroom as one common zone allocates the bedroom dwelling activity to that zone. The number of residents is defined based on their presence in the building and is selected as a default number in the DesignBuilder software. The metabolic rate is calculated based on the type of activity. Following ASHRAE standards, the metabolic rates for men, women, and children are 1.00, 0.85, and 0.75, respectively. Since this research focuses on residential buildings, the averaged rates were adopted (Standard, ASHRAE/ANSI, 2013).

Construction parameters

In the construction template, based on the available optimized easily accessible features, the external windows, lighting systems, recessed areas, radiant fraction, visible fraction, and the HVAC system were defined from a software library based on zone types and common construction building in Iran. Here, authors selected the fan coil system as the HVAC, and the mechanical ventilation operation schedule was determined based on zone type. The HVAC system did not apply to unserved zones such as parking, all stairs, and the patio. The structures of walls, roofs, and floors of each zone are defined in Table 3. They are determined based on architectural and structural plans in a narrow sense. To make significant progress toward the research goal, only one generic roof and one-floor type were selected for this project. Only the building's external walls varied. This research investigated common building materials in terms of energy analysis and construction costs and concluded with a presentation of the optimum building envelope structures.

Flat roof structures are defined as block joist roofs, which include six layers, including mosaic tile with 25 mm thickness, EPS with 100 mm thickness, bitumen with 5 mm, a concrete slope of 5 mm, a block of 300 cm, and gypsum plastering with a thickness of 30 mm. Detailed information is presented in Appendix 1.

External Walls

External wall details are generated as a new template loaded into the model to achieve the project aim. The common building materials, including block, brick, insulating materials, and plasters, and all common building wall structures were investigated. This project was examined in one climate. The properties of each material are described in Appendix 2, and the properties of generated wall layers are presented in Appendix 1.

Adjacency

The surfaces' adjacency is either automatically adjacent to the outside environment or is conserved as adiabatic. The east and west sides of the selected building's external walls are considered adiabatic, and the north and south side is considered auto adjacent to the outside environment.

3.4 Assumptions

After evaluating the common building plan and wall structures in Iran, a realistic analysis of the specific work scope was developed, covering common practical limitations for Iran's residential buildings. These limitations are:

- The total interval thicknesses of external walls are between 20 and 40 cm,
- The analysis covers one climate zone,
- The thickness of insulating materials is limited to 5 cm based on executive criteria,
- All possible and common wall structures investigations are based on executive criteria,

3.5 Effective factors on external wall structures

To achieve the optimum external wall structures, we determined the primary factors that affect the building's energy performance on the entire external wall structure to be:

- Type
- Material
- Thickness

TABLE 3. Construction Parameters.

External Window	Double glazing-reflective-clear-6 mm air with 30% glazing
Lighting system	T8 (25 mm diam.)—fluorescent—halophsphate
Recessed Type	luminaire
radiant fraction	0.37
visible fraction	0.180
HVAC System	fan coil
Flat roof	block joist roof

- Dimension
- Insulation Type
- U-value of each material
- Execution of wall structures;
- Total Cost

3.5.1 External Walls Details

This research is mainly focused on investigating 58 various external wall patterns to find layer combinations that can produce the most energy efficiency for the external wall structure. It is worth noting that after thorough research among different local companies for building external walls, all the possible alternatives were identified, with only 58 different types. These 58 alternative wall structures are extracted from the comprehensive study based on the common construction methods executed in Tehran, Iran.

According to Iran's common construction methods, two types of external wall execution in the traditional combinations were implemented, with and without insulation materials. The Iranian construction industry has a variety of building materials to choose from. The common building envelope materials in Iran were considered in this research. These include autoclaved aerated concrete (AAC) blocks; the light expanded clay aggregate (LECA), Perflex blocks that are composed of primary materials, such as Perflex lightweight (PLW) and Perflex ultra-weight (PUW) concrete, solid brick, clay blocks (CBs), cement blocks (CMBs) and 3D walls. The insulating materials applied in double-wall include expanded polystyrene (EPS), extruded polystyrene (XPS) by air, XPS by hydrochlorofluorocarbons (HCFC), XPS by chlorofluorocarbons (CFCs), glass wool, and Rockwool. To better understand wall structures, detailed sections, and properties, detailed information for two wall structures (as examples from Appendix 1) is shown in Figure 6 and Figure 7, as well as Table 4 and Table 6. Also, the thermal properties of the two wall structures are described in Table 5 and Table 7. Technical specifications of building materials were gathered from building supplier companies. Thermal properties related to other wall alternatives, the material properties, and costs are given in Appendix 1 and Appendix2.

3.6 DesignBuilder Software Validation for Building Energy Analysis in Iran:

The DesignBuilder simulation software had to be validated by the Building Energy Simulation Test for Existing Home (BESTEST-EX) procedure developed by the International Energy

FIGURE 6. Wall Type 25 Layout, DesignBuilder.

FIGURE 7. Wall Type 46 Layout, DesignBuilder.

TABLE 4. Wall Type 25 Layers, DesignBuilder.

Layer	Width (mm)	Density (kg/m^3)	Conductivity (w/m·k)	R-Value (w/m^{2}k)	Embodied Carbon (kg Co_2/kg)
Cement Plaster, Sand aggregate	30.00	1860	0.720	0.042	0.19
Clay Block	200.00	—	—	0.39	0.33
Gypsum Plastering	30.00	750–900	0.25	0.12	0.38

TABLE 5. Wall Type 25 Thermal Properties, DesignBuilder.

Thermal Properties, Wall Type 25	
R-value (m^2·k/w)	0.722
U-value (w/m^2·k)	1.386

Agency. BESTTEST-EX is a test procedure using building physics and utility bill calibration to evaluate the tool's energy simulation performance.

4. CASE STUDY VALIDATION

4.1.1 Building Specification of Case Study

The authors have analyzed a generic building validating this study's framework. The studied building consists of three floors with brick facing. The building structure is a steel structure

TABLE 6. Wall Type 46 Layers, DesignBuilder.

Layer	Width (mm)	Density (kg/m^3)	Conductivity (w/m·k)	R-Value (w/m^{2}k)	Embodied Carbon (kg CO_2/kg)
Cement Plaster, Sand aggregate	30.00	1860	0.720	0.042	0.19
Cement Block	75.00	—	—	0.070	0.33
Expanded Polystyrene Styrofoam	50.00	13–15	0.047	1.064	2.50
Cement Block	75.00	—	—	0.070	0.33
Gypsum Plastering	30.00	750–1000	0.25	0.12	0.38

TABLE 7. Wall Type 46 Thermal Properties, DesignBuilder.

Thermal Properties, Wall Type 46	
R-value (m^2·k/w)	1.536
U-value (w/m^2·k)	0.651

with a roof covering the barrel vault system. The built-up area of the building is 495 m^2. The building's orientation is facing towards the north. It is residential and adjacent to buildings from both east and west sides. The heating system is a radiator, and the cooling system is a roof-mounted cooler.

4.1.2 Energy Analysis

All of the design parameters are modeled, and effective parameters are defined to simulate the energy consumption of this building in the Tehran, Iran region. Finally, the output results from simulation compared with the actual annual energy consumption gathered from monthly utility bills over a year of an existing building.

Non-construction Parameters

One of the floors is completely described, and the recurrence is avoided due to similar characteristics of floors. The floor includes bedrooms, living room, kitchen, stairs, restrooms, and bath. The parameter details are presented in Table 8 based on ASHRAE Standard (American Society of Heating, Refrigerating and Air Conditioning Engineers, 2007).

Construction Parameters

The construction parameters specification are proposed in Table 9. The considered HVAC system consists of two separate heating and cooling systems. The cooling system in the current building is a roof-mounted cooler with a capacity of 7000 m^3/hour, and evaporating cooling with the following features is applied.

The roof of the building consists of layers, including slate tiles with 20 mm thickness, cement plaster with 20 mm thickness, natural light aggregate with 20 mm thickness, brick with 100 mm thickness, and gypsum plasterboard with 25 mm thickness. The ground floor

TABLE 8. None construction Parameters Specification for different zones.

Bedroom Zone	
Occupancy	0.05 people/m^2
heating set point in winter	24 °C
heating set back	20 °C
Living Room Zone	
Occupancy	0.06 people/m^2
heating set point in winter	24 °C
heating set back	20 °C
Kitchen Zone	
Occupancy	0.15 people/m^2
Toilet-Bath Zone	
Occupancy	0.01 people/m^2

TABLE 9. Construction Parameters Specification.

External Window	**single pane clear-3 mm, Aluminum window frame, no glazing**
Shading	None
Lighting system	T8 (25 mm diam.)—fluorescent
HVAC System—Cooling system	roof-mounted cooler—capacity of 7000 m^3/hour
electricity consumption for electromotor of cooler	560w
HVAC System—the heating system	Radiator
Flat roof	barrel vault system with natural lightweight aggregate
external wall structure	brick walls

is adjacent to the ground consists of clay, tiles, and cement plaster with a U-value of 2.132 w/m^{2}k. The detailed properties of the wall structure are shown in Appendix 4.

4.1.3 Results of Energy Simulation

The building energy simulation shows that the amounts of annual gas and electricity consumption of energy simulation are 97705.06 kWh and 11659.45 kWh, respectively.

As shown in Table 10, the amount of annual gas and electricity from the utility bills is 9717 m^3 and 11622 kWh. The actual building energy consumption is gathered from monthly gas and electricity bills. It is worth mentioning that the simulated annual gas consumption

TABLE 10. Annually Gas and Electricity Consumption of actual building (kWh).

Month	Gas Consumption (m^3)	Electricity Consumption (kWh)
January	1529	1278
February	1640	1278
March	514	771
April	310	771
May	294	822
June	500	822
July	600	1227
Aguste	473	1227
September	1155	969
October	1302	969
November	1400	735
December	1700	735
Annual Consumption (kwh)	9,717	11,622
Simulated Consumption	97,705.06/10 = 9,770.51	11,659.45
Difference	0.55%	0.32%

by DesignBuilder is based on kWh. In contrast, the annual gas consumption derived from the energy consumption bill is based on m^3—noted that 1 m^3 gas is almost equal to 10 kWh (Learning metrics HVAC system based on the specification, n.d.). The closeness of actual energy consumption and energy simulation values reveals that the DesignBuilder is validated for energy analysis of buildings in the Tehran, Iran geographical region.

5. RESULTS AND DISCUSSION

This project's energy analyses are presented in this section. Material cost was considered a significant parameter parallel to building energy performance to present the optimum external wall type. Energy analysis output diagrams and a discussion of results are comprehensively stated for each parameter.

5.1 Building Material Cost

Technical specifications of the building materials used in this study, specifically the building envelope, were obtained from local building supply companies. The gathered information on cost estimation for each building material is mentioned in Appendix 2 based on their material types. The material costs of the double-wall structure were higher than the single-wall structure. Note that the material costs of gypsum and cement plastering are calculated in the external walls' total material costs and are considered equal to 39,000 Rials or 93 cents (US currency) per m^2. To better understand how material costs are calculated, we show two examples in Table 11.

The material cost of an external double and single wall based on Appendix 2 is presented in Table 12 and Table 13.

Based on building material cost tables, the maximum cost of wall materials belongs to 2AAC12.5-5XPS (CFC) and 2AAC12.5-5XPS (HCFC) with 579,000 Rials per m^2 (\$13.75 per m^2), and the minimum cost was obtained by using 16 clay blocks with 133,350 Rials per m^2 (\$3.17 per m^2).

5.2 Energy Analysis Result

After applying 58 alternatives for energy simulation of building envelope and validating the DesignBuilder® software package, the outputs are presented based on construction types. The considered insulation material types are the significant focus of these results. The graphs belong

TABLE 11. Material Costs of 2 External Walls (Rial per m^2).

Material	Dimensions (cm)	Material Cost (Rial per m^2)/(US Dollars per m^2)
AAC12.5	60 × 25 × 12.5 cm	177,500 (\$4.22)
PU150	60 × 25 × 15 cm	195,000 (\$4.63)
XPS (CFC*) Insulation	5 cm	185,000 (\$4.39)
Gypsum and cement plastering	6 cm	39,000 (\$0.93)
2AAC12.5 + 5XPS (CFC)	36 cm	(2 * 177,500) + 185,000 + 39,000 (Plastering price) = 579,000 (\$13.75)
PUW	21 cm	195,000 + 39,000 = 234,000 (\$5.56)

*XPS extruded by CFC; Colorofolorocarbon

TABLE 12. Total Material Costs of Single External Wall (Rial per m^2).

Wall Structure	Single Wall 15 cm	Single Wall 17.5 cm	Single Wall 20 cm	Single Wall 28 cm	Single Wall 38.5 cm
AAC	252000	287500	323000	—	—
LECA	255000	304950	270750	—	—
PLW	224000	—	284000	—	—
PUW	234000	—	294000	—	—
CB	133500	—	144000	—	—
CMB	138,000	—	171,000		—
Brick	—	—	—	223850	—
3D Wall	—	—	—	—	261000

TABLE 13. Total Material Costs of Double External Wall (Rial per m^2).

Wall Structure	EPS Insulation	XPS (Air) Insulation	XPS(HCFC) Insulation	XPS(CFC) Insulation	Glass Wool Insulation	Rock Wool Insulation
2CB7.5	249200	344200	354200	354200	274200	294200
2CB10.5	257600	352600	362600	362600	282600	302600
2CB12.5	266000	361000	371100	371000	291000	311000
2CMB7.5	229000	324000	334000	334000	254000	274000
2CMB10.5	273000	368000	378000	378000	298000	318000
2AAC10	403000	498000	508000	508000	428000	448000
2AAC12.5	474000	569000	579000	579000	499000	519000

to walls with different wall thicknesses, and insulated materials are presented based on material insulation types. Note that the total energy consumption (TEC) is based on the energy usage of the HVAC (heating, ventilation, & air conditioning) in one year.

5.2.1 Double Wall Structures

Figure 8 and Figure 9 show that the double walls' graphs indicate that the best energy performance belongs to the 2AAC block when the wall is insulated with insulation materials. The maximum amount of TEC belongs to 2 CMB 7.5 with 5 cm of insulation materials.

Based on the alternatives of double-wall graphs, it was found that the wall combination with 2AAC Block 12.5 has better energy performance than all of the other wall structures. The best energy performance belongs to the 2AAC12.5 block with XPS (CFC) insulation. In terms of energy efficiency or total energy consumption (TEC), the double-wall with AAC12.5 cm with 5 cm XPS (HCFC) and XPS (air) had the second and third best ratings, respectively.

FIGURE 8. Total energy consumption (TEC) of the double external wall (kWh).

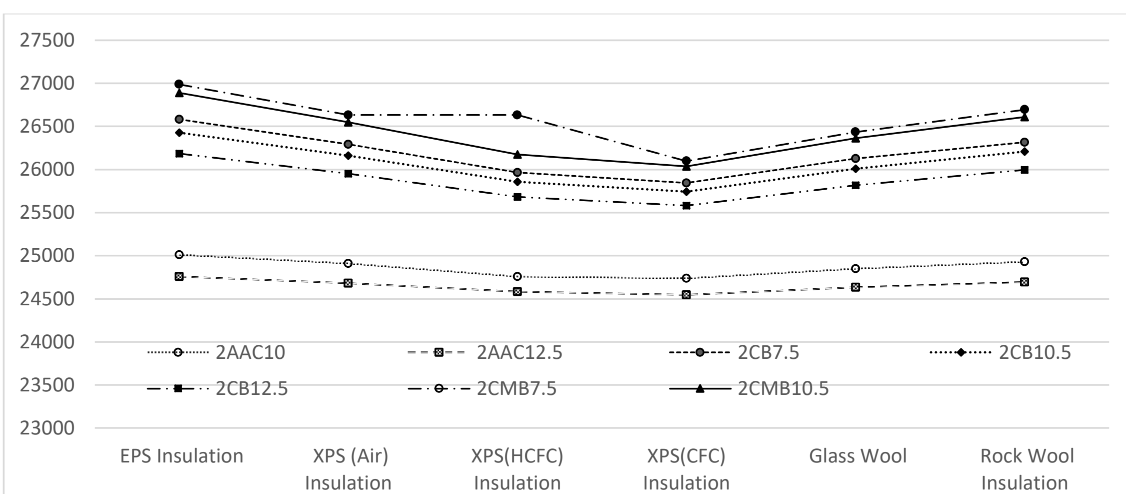
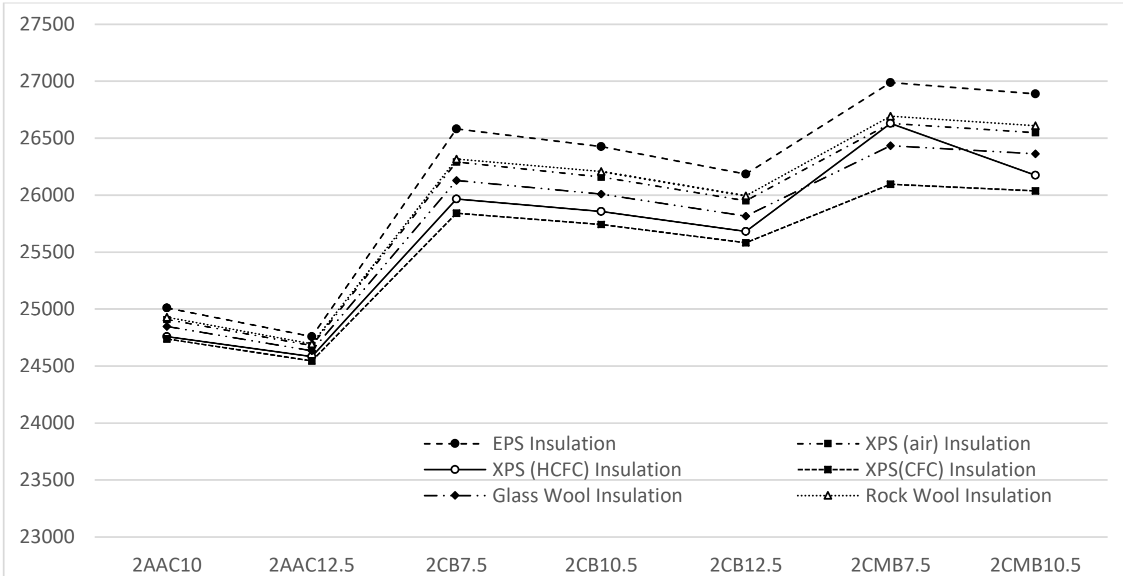


FIGURE 9. Total energy consumption of double external wall (kWh) based on insulation types.



The EPS insulation material had the poorest energy rating, as shown in Figure 10. TEC of AAC block and double wall with insulation materials. To evaluate insulation materials' energy performance precisely, the heat loss through the wall referred to each double wall with specific insulation materials, as shown in Table 14.

5.2.2 Single Wall without Insulation Material

To measure the single wall alternatives in the current research, the single walls are compared in total energy consumption based on specific wall thicknesses. Therefore, the related graphs with the considered single-wall alternative types for external use are presented based on wall thicknesses. The wall thickness is the mean of the core thickness (average) regardless of plastering

FIGURE 10. TEC of AAC block and double wall with insulation materials.

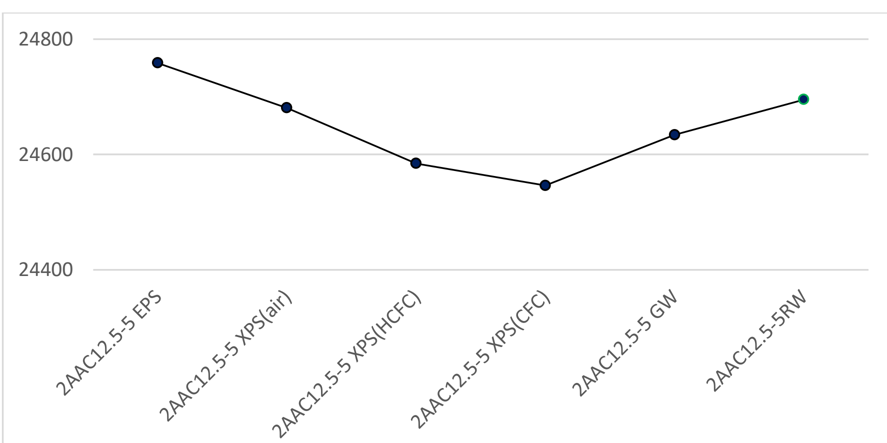


TABLE 14. TEC of AAC block and double wall with insulation materials.

Double Wall	TEC (kWh)	Heat Loss (kWh)	CO_2 Emission (kg)
2AAC12.5-5XPS(CFC)	24546.15	–851.30	33894.64
2AAC12.5-5XPS(HCFC)	24584.33	–869.17	33906.31
2AAC12.5-5GW	24634.05	–892.07	33921.74
2AAC12.5-5XPS(air)	24680.73	–913.97	33936.10
2AAC12.5-5RW	24695.29	–920.75	33940.57
2AAC12.5-5EPS	24758.84	–950.36	33960.11

layers, but these are considered in the numerical simulation. Thus, total wall thicknesses are mentioned in the final analysis.

As shown in Figure 11, a single wall's best energy performance with 15 cm thickness belongs to the PERLEX block ultra-weight. The AAC, PERLEX lightweight, LECA, clay, and cement block performances are placed after that in descending rate of efficiency.

In evaluating a single wall's energy analysis with a 15 cm thickness, the PERLEX ultra-lightweight block had the best energy performance compared to the other types of walls. The TEC reduction percent of this block compared to different types of walls is mentioned in Table 15.

As mentioned in the single wall's energy analysis with a 15 cm thickness, the PERLEX ultra-lightweight block exhibits the best energy performance. This system's heating and cooling energy consumption for bricks are 20772.8 and 12507.17 kWh, respectively. The TEC of this option is 33279.97 kWh. Still, this material does not apply in the current market in the

FIGURE 11. Total energy consumption of single external wall (kWh).

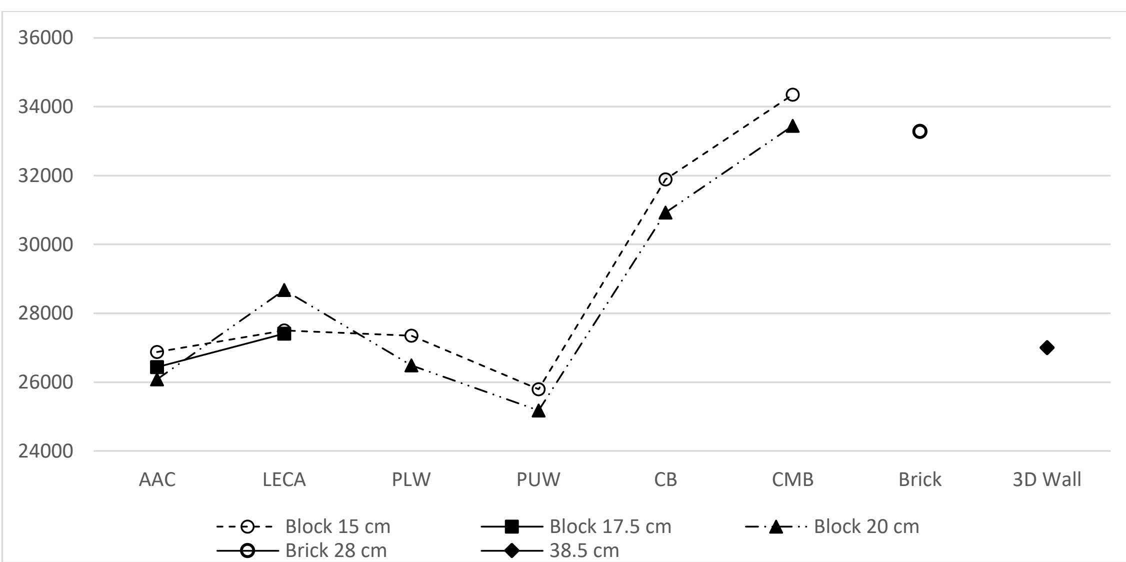


TABLE 15. Comparison of single wall.

Single Wall Structure	TEC (kWh) Single wall 15 cm	TEC (kWh) Single wall 17.5 cm	TEC(kWh) Single wall 20 cm
PUW	25791.81	—	25177.39
AAC	26875.56	26434.1	26082.24
PLW	27346.95	—	26490.39
LECA	27498.85	27409.75	28672.62
CB	31885.39	—	30927.23
CMB	34350.09	—	33445.15

TABLE 16. The comparison of a 3D wall, clay block, and cement block.

Wall Structure	Core thickness (cm)	R-Value (m^2k/w)	TEC (kWh)
3D Wall	16.00	1.483	27001.61
Clay Block	15.00	0.632	31885.39
Cement Block	15.00	0.472	34350.09

current market due to its heavyweight, so the brick total energy consumption in this analysis was not included. The energy output related to the brick structure can be found in Appendix 3. When comparing a single wall's energy performance with 17.5 cm thickness, the AAC had a better energy performance than the LECA block. As shown in Figure 11 and Table 15, the PERLEX block had the best energy performance when considering the wall's thickness of 20 cm with 25177.39 kWh total energy consumption. The cement block exhibits a poor energy performance with 33445.15 kWh TEC.

The 3D wall system with a total wall thickness of 22 cm is considered a new construction system. The analysis does not consider a thermal bridge in the current simulation. This system's heating and cooling energy consumptions are 15815.63 and 11185.98 kWh, respectively. The heat loss through the 3D wall is –783 kWh. The TEC of a 3D wall is 27001.61 kWh. A 3D wall is compared to traditional building materials in Table 16.

6. OPTIMIZATION

To present optimum external wall structures, the analysis of the total energy consumption of a BIM building's HVAC system in all the external wall alternatives is presented in parallel with the material costs. The energy consumption and cost are crucial parameters in the current analysis and are simultaneously considered in some different wall thicknesses. The final analysis of the results is completely presented. A numerical comparison is achieved to achieve this aim, and the best option is clearly stated. The external wall's total energy consumption and all the alternatives' material costs are summarized in Table 17 and Table 18.

TABLE 17. Optimum double external walls with specific wall thicknesses.

Wall Structure	External Wall Thickness (cm)	EPS Insulation	XPS (Air) Insulation	XPS(HCFC) Insulation	XPS(CFC) Insulation	Glass Wool Insulation	Rock Wool Insulation
2CB7.5	26.00	0.015	0.0174	0.0176	0.0176	0.0156	0.0161
2CB10.5	32.00	0.0153	0.0176	0.0178	0.0177	0.0157	0.0163
2CB12.5	36.00	0.0154	0.0177	0.0179	0.0179	0.0159	0.0164
2CMB7.5	26.00	0.0146	0.017	0.0171	0.0171	0.0152	0.0158
2CMB10.5	32.00	0.0158	0.0181	0.0183	0.0182	0.0162	0.0168
2AAC10	31.00	0.0185	0.021	0.0211	0.0211	0.0192	0.0197
2AAC12.5	36.00	0.0203	0.0227	0.0203	0.023	0.0209	0.0214

TABLE 18. Optimum single external walls with specific wall thicknesses.

Wall Structure	Single Wall 15 cm	Single Wall 17.5 cm	Single Wall 20 cm	Single Wall 28 cm	Single Wall 38.5 cm
AAC	0.0152	0.016	0.0169	-	-
LECA	0.0155	0.0168	0.0163	-	-
PLW	0.0147	-	0.0159	-	-
PUW	0.0145	-	0.0158	-	-
CB	0.0138	-	0.0137	-	-
CMB	0.0147	-	0.0152	-	-
Brick	-	-	-	0.0166	-
3D Wall	-	-	-	-	0.0155

Legend

Lowest Amount — Highest Amount

In the current research, the optimum function is defined as:

$$\text{Optimimazion function} = \min(E + C)$$

E is total energy consumption, and C is a material cost for external walls. The TEC and material costs are normalized, as seen below, and the final results are shown in Table 17.

All material costs are divided by the average material cost, and the TEC amounts are divided by the TEC average to reach rounded-off unit amounts. For example, the external wall 2ACC12.5-5XPS (CFC) has a 32 cm thickness with a total energy consumption of 24546.15 kWh. The cost is 579,000 Rials per m^2 (\$13.75 per m^2). The average TEC in 58 alternative external walls was 26590.5 kWh. The average external wall cost of the 58 alternative walls was 333387.1 Rials per m^2 or \$7.92 per m^2. The total energy values were made dimensionless by dividing the 24546.15 kWh by 26590.5 kWh for 0.923 kWh. Construction costs of the external walls are made dimensionless by dividing 579,000 by 333387.1 for 1.74 Rials per m^2 or 41 cents (in US currency) per m^2.

To normalize total energy consumption: 0.923/116 kWh = 0.0080 kWh

To normalize material cost: 1.74/116 = 0.0150

The normalized $\sum E + C$ coefficient is $\sum E + C = 0.0080 + 0.0150 = 0.0230$

Based on the optimization results, the clay block wall structure with 15 cm core thickness is determined as optimum for the external wall. Note that this optimization is determined based on the minimum summation of total energy consumption and material costs.

7. CONCLUSIONS AND FUTURE WORK

The BIM building envelope is a primary element between a BIM building's internal and external environment, impacting building energy efficiency significantly reducing energy consumption. This research emphasized evaluating the energy performance of common building materials in a building envelope. The methodology was to achieve this aim based on the generation of a generic model made in Autodesk Revit® and an energy analysis conducted using DesignBuilder®. In this regard, 58 alternative external wall structures with combined common building materials were used to evaluate a BIM building envelope energy analysis.

Energy consumption involving building and material energy efficiencies and costs, as crucial parameters, substantially affect design decision-making. The optimization function is proposed to assist designers select building materials for external wall structures of building envelopes based on their contribution to energy efficiency (i.e., less energy consumption than other materials). The possible alternatives were defined based on thickness, thermal properties, and construction types. All alternatives were analyzed, and the output results are reported herein.

The external wall combination was considered capable of using two construction types during the modeling process, including single and double walls. After energy simulation, the outputs showed that the double external wall structure, the wall with the core built of AAC blocks, had a thickness of 12.5 cm. The XPS (CFC) insulation material had an energy performance better than the other external double-wall structures. It showed a 10% reduction in total energy consumption compared with the same core structure and EPS insulation material. In the single external wall analysis, with 15–20 cm thicknesses, the PERLEX ultra-lightweight (PUW) wall had better energy performance compared to the other building materials tested in this research, see Table 19 and Figure 12. The AAC block wall with the same thickness came in second in TEC, but it had more comprehensive resistance than the Perflex block wall, which had a 25% reduction in total energy consumption (TEC) compared to a cement block wall. The AAC block wall, when compared to the LECA block, had a 3% energy consumption reduction. Compared to the cement block, the AAC block had a 21% reduction in energy consumption. The 3D wall had a 15% reduction in TEC compared to the clay block wall and a 21% reduction compared to a cement block wall. These reduction percentages were determined concerning other effective parameters and are considered ideal options. Note that the building envelope behaves as an integrated structure.

To present an optimum external wall structure, the analysis of the total energy consumption of a BIM building's HVAC system in all external wall alternatives was considered in parallel with the building material costs. The optimization function determined the minimum total energy consumption of the external wall structure and the building material cost. From optimization results, the optimum wall structures were based on specific total wall thicknesses in descending order, with the best wall presented first:

- External wall with 21 cm total thickness: Clay block, PUW, PLW, Cement block, AAC, and LECA.
- External wall with 26 cm total thickness: Single wall: Cement blocks Double Wall: 2CMB7.5-5EPS, 2CB7.5-5EPS, 2CMB7.5-5GW

Based on the optimization results, the clay block wall structure with a 15 cm core thickness is determined as an optimum external wall, see Table 19 and Figure 12. To have an energy-efficient external wall structure, it is clear that the structure's weight in building energy performance is important. The weight of both parameters (TEC and material cost) is considered equal. Based on this optimization function, each parameter's importance is considered based on the employer's discretion. There is no preference between these two parameters in the current research when determining the optimum external wall structure.

The applicability of the suggested approach is validated with a case study of a typical residential building. The results suggest that the DesignBuilder is validated for energy analysis of buildings in Iran due to the closeness of actual energy usage and energy simulation values as mentioned in section 4.1.3.

To better understand, the schematic graphical presentation of the developed external wall structures with the detailed information for the best external wall combination layers in Double wall, Single Wall are stated in Figure 12 and Table 19. Also, the sectional view of the optimum wall structure considering the TEC and cost parameters is presented.

7.1 Research Limitations:

One of the limitations of the present study is using the generic building plan; however, this is based on the survey of the common buildings. The authors only considered one building form

FIGURE 12. Candidate Wall Structures Layout.

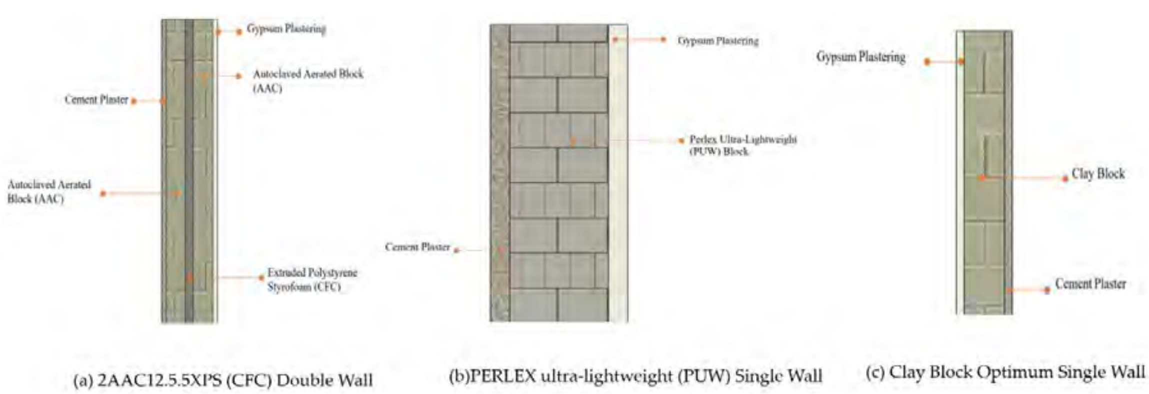


TABLE 19. Candidate Exterior Wall Layers Detail Information and Thermal Properties.

Item	Layer	Width (mm)	Density (kg/m³)	Conductivity (w/m·k)	R-Value (w/m²k)	Embodied Carbon (kg Co_2/kg)	Thermal Properties of Exterior Wall	
							R-value (m²·k/w)	U-value (w/m²·k)
(a) 2AAC12.5.5XPS (CFC) Double Wall	Cement Plaster, Sand aggregate	30.00	1860	0.720	0.042	0.19	3.936	0.254
	AAC (Autoclaved Aerated Block)	125.00	450–550	0.12	1.042	0.33		
	Extruded Polystyrene Styrofoam (CFC)	50.00	25–40	0.033	1.52	2.88		
	AAC (Autoclaved Aerated Block)	125.00	450–550	0.12	1.042	0.33		
	Gypsum Plastering	30.00	750–900	0.25	0.12	0.38		
(b) PERLEX ultra-lightweight (PUW) Single Wall	Cement Plaster, Sand aggregate	30.00	1860	0.720	0.042	0.19	2.12	0.452
	Block PERLEX (Ultra-Light Weight)	150.00	450	0.08	1.88	0.33		
	Gypsum Plastering	30.00	750–900	0.25	0.12	0.38		
(c) Clay Block Optimum Single Wall	Cement Plaster, Sand aggregate	30.00	1860	0.720	0.042	0.19	0.632	1.583
	Clay Block	150.00	—	—	0.30	0.33		
	Gypsum Plastering	30.00	750–900	0.25	0.12	0.38		

(i.e., rectangular) and one specific heating and cooling system. Besides, this research focuses on evaluating the various building envelopes considering exterior wall structures. Other building elements (i.e., floor, window, ceiling) are optimum. Moreover, based on Iran's construction methods, the thickness of external wall structures is restricted to be within 20 and 40 cm, and the thickness of the insulation material is considered 5 cm. As this study focuses on building materials' energy efficiency, the research is just determined for one climate zone. This study does not consider constructability, quality control, and execution time.

7.2 Future research

Based on the current research, which is based on one generic model in a specified climate of Iran, a list of recommendations for future study includes the following:

1. Determining optimum daylight considering the ratio of window to the wall in facades of various climates and comparing with LEED criteria,

2. Comparing the energy consumption of buildings with the embodied energy of materials during each building's life span,
3. Although the annual energy analysis has been conducted nonetheless, day-by-day and hour-by-hour data should be reviewed to determine the software's accuracy and preference for future research. Evaluating energy consumption of common roof structures in buildings,
4. Thermal comfort analysis of buildings based on resident satisfaction,
5. Considering other effective parameters to achieve optimum building envelopes, and
6. Evaluating building material wastes with BIM.

Some of the concerns explored in this study may need to be solved in the future; for example, this paper only looked at one building type that used single file formatting for data sharing. There were still some areas that required manual intervention at some stages during the process. All of these areas require greater exploration and are accessible to future research.

The future demand in this area should be for the automatic creation of data from BIM models for simulation of building sustainability studies using modern computational approaches such as Dynamo and Grasshopper. This approach will improve the decision-making process and boost the amount of automation dramatically. Moreover, the thermal transmittance (heat and moisture) in walls made of different layers can be more accurately analyzed by implementing sensors such as heat flux sensors (Xinrui Lu, 2018) through dynamic models to achieve optimum thermal comfort conditions in buildings.

DATA AVAILABILITY STATEMENT

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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