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Identification and Prioritization of Energy Consumption Optimization Strategies in the Building Industry Using the Hybrid SWARA-BIM Model

Abstract

Energy consumption in buildings has become one of the most critical problems in all countries and principles of sustainability suggest that a satisfactory solution must be found to reduce energy consumption. This study aims to identify and prioritize energy consumption optimization strategies in buildings. Data collection consists of gathering primary data from the existing literature and secondary data from interviews, questionnaires, and simulations through building information modeling (BIM) tools. Twenty-nine strategies were identified and categorized into five groups according to their nature and ranked using one of the multiple criteria decision-making (MCDM) methods called the step-wise weight assessment ratio analysis (SWARA). A case study building in Shiraz, Iran, was simulated using BIM software, and the energy saving potential of the highest ranked strategies were obtained. According to the results, significant contributors to the energy consumption optimization were "Using renewable energy resources," "Using efficient insulation," and "Using suitable materials," providing 100%, 35%, and 23% efficacy, respectively. The results obtained from this study can inform the building industry's key stakeholders regarding the best strategies to apply in order to reduce energy consumption and improve sustainability in the construction industry.

Keywords

Building information modeling (BIM); simulation; energy efficiency; sustainability; MCDM method.

1. Introduction

Human activities are widely known as the most influential contributors to climate change, particularly the emissions of greenhouse gases that they produce. They are also one of the main factors behind global warming. Therefore, changes are needed in the energy consumption, housing, mobility, and food sectors to reduce the negative consequences of human activities. Buildings, meanwhile, have an essential role in creating climate change since they produce more than 8.6 million metric tonnes of CO_2 each year [1]–[4]. Buildings consume over 40% of global energy, 30% of natural resources, and produce 30% of anthropogenic greenhouse gasses. As a result, there is considerable pressure to embrace sustainable constructions which will undoubtedly become a growing market in the construction industry's future [2], [5]–[8].

Currently, more than 50% of the world's population lives in cities, and this number will reach nearly 70% by 2050. It is anticipated that city residents will consume approximately 75% of global energy and emit around 70% of the world's carbon dioxide [9]. Researchers have delved into the concept of energy and introduced several solutions to improve energy efficiency in buildings, including smart energy management [10], passive building design [10], the use of low energy materials, the installation of efficient types of equipment, and the integration of renewable energy technologies [7]. For instance, some researchers have proposed using active and passive energy consumption optimization strategies [3], [12]–[17]. Another solution can be the construction of zero or positive energy buildings (ZEBs or PEBs). In net-zero energy buildings (NZEBs) or ZEBs, local renewable energy production is balanced according to annual energy consumption. Consequently, the annual energy consumption of such buildings from the energy grid would be close to zero [9], [18], [19]. Thanks to existing advanced technologies [20], the same concept can be extended at the settlement or precinct level to achieve cost benefits, as demonstrated by [21], If the design, construction, and maintenance phases of building construction projects take place according to the concept of sustainability, a significant amount of energy can be saved in countries. To do so, the proper evaluation of alternative designs, selection of systems and materials, allocation of the energy budget, compliance with energy standards, and economic evaluations are necessary [22].

An integrated study investigating all the energy-saving strategies applied to a building is preferable to the investigation of each strategy separately. Several studies have been conducted considering a limited number of parameters such as the building's lifecycle [23]–[28], carbon dioxide emissions [29]–[34], and the thermal comfort of residents [35]–[40], in which different perspectives and analysis methods including MCDM methods were used [5], [13], [41], [42]. However, few studies have conducted a thorough analysis in which a large number of design parameters are discussed and analyzed simultaneously. Meanwhile, several previous studies have suggested using BIM and life cycle assessment (LCA) for integrating modeling and assessment to quantify and reduce detrimental effects as well as simplifying data optimization [19], [41], [43], [44].

According to the U.S. National BIM standard, BIM is defined as a shared knowledge resource for reliable information basis during the building lifecycle [42]. BIM includes several different dimensions representing various stages of the project and can play a significant role in the comprehensive perspective of designers and stakeholders. The third dimension of BIM (3D) refers to the three-dimensional characterization of the building objects [45]. The fourth dimension (4D) refers to time management, which is analyzed by time scheduling methods. The fifth dimension (5D) considers the modeling of costs, and more specifically, the lifecycle costs of the building [46]–[48]. The sixth dimension (6D) of BIM is related to the environmental behavior and sustainability of the building. The seventh and last dimension (7D), refers to maintenance schedules and facility management [49].

Although sustainability and BIM take place in the 6D modeling stage, other dimensions can also affect the sustainability performance of the project. Since the definition of sustainability and its global awareness have altered over time, it is possible to view aspects such as cost, comfort and other parts of BIM influencing the sustainability of projects [49]. However, the energy consumption and thermal aspects of buildings are key elements of sustainability, and they should be categorized in 6D BIM. [50].

Even though there are many studies on reducing energy consumption in buildings, few studies have used integrated modeling that can provide an extensive perspective on the design process. The capability to achieve a holistic view of the energy consumption factors, together with gaining insight over all stages of the building construction, has been regarded as a gap in the body of knowledge.

This study aims to identify the strategies that contribute to the total energy consumption of buildings and quantify the effect of utilizing each strategy on reducing energy use. In this research, energy reduction strategies were identified using different literature review methods and interviews. A questionnaire was then used to prioritize the strategies by asking building industry experts' opinions. An integrated model was employed using BIM software to explore the interrelation between the factors and the total energy consumption of the candidate building. The novelty of this research is drawing upon a comparison of the efficacy of all the strategies which can be used to reduce the energy consumption of the building. This integrated approach, together with a multi-dimensional BIM model, can give the designers and stakeholders the ability to select the best strategy.

2. Literature review

Several studies mention the policies and technologies needed to create a schematic approach for managing the critical building information and other specifications of BIM. Nevertheless, despite the growing research on BIM and its underlying potential for implementing sustainability, the development of green BIM is still immature and unsystematic [41]–[43].

Chel and Kaushik in [7] discuss four main aspects of energy-efficient buildings, that is, passive design, low embodied energy materials, efficient appliances, and integration of renewable energy technologies. The best time for enhancing the energy efficiency of buildings is before the construction phase. Although [7] has interesting findings on passive energy principles and the urgent need to use renewable energy, just a handful of parameters are investigated in the manuscript.

Gaffarianhoseini et al. [51] introduce a conceptual framework with several modules for developing software solutions for the energy management of buildings. The framework aims to evaluate sustainability performance during the post-construction stages. This study identifies the interoperability of the framework by standardizing communication protocols, data formats, naming conventions, evaluation systems, and modularization. Such a solution is expected to improve post-construction energy efficiency and maintenance effectiveness. However, the research does not use a case study to show the implementation of the proposed framework in an actual project [51].

Hosseini et al. [52] investigated the barriers to BIM adoption and ranked the causes contributing to the disuse of BIM in construction projects in Iran based on a questionnaire survey. It comes to light that less than 30% of the country's construction practitioners are involved in some level of BIM and more than 36% even do not have any plans to adopt BIM in the near future. Their findings show that barriers, such as the standards and guidelines, lack of knowledge and attention from the policymakers, and lack of support from managers can hinder the BIM adoption in the building industry. In [52] it is concluded that governors should control the business environment and should pay specific attention to measures promoting BIM and sharing the knowledge collected throughout the construction industry. These findings are based on a specific project in the capital city which might not be representative on a country-wide scale [52].

Shadram and Mukkavaara studied in [19] the trade-off between operational and embodied energy for different materials in a BIM framework, and used a low-energy case study building in Sweden to show the potential for reducing life cycle energy demand. Their semi-automated optimization process enables a reduction in the time, effort, and risk of mistakes during the manual data input and output through BIM software. The results show an estimated reduction of 140 GJ of operational energy reduction can yield a 340 GJ increase in the quantity of embodied energy in the case study. The optimal reduction of an estimated 108 GJ for operational energy is the equivalent of 4 to 8 years of operational energy in the initial design. The embodied impact caused by transportation of building materials to the construction site, on-site construction processes, operational maintenance, and demolition is excluded [19].

Nizam et al. [53] proposed a framework to estimate the embodied energy in the BIM environment. This procedure is implemented by calculating material embodied energy, transportation energy, and construction energy. The results show that the share of material embodied energy in buildings is much higher than transportation and construction energy. The researchers concluded that using suitable materials can be an advantage for enhancing the energy efficiency of buildings [53].

Gerrish et al. used interviews to probe the application of BIM in the energy performance management of buildings [54]. The research intended to identify barriers to BIM for designers and operators as a performance optimization tool. The method is supplemented by interviews with designers and also a real-world example. The results show that barriers such as technical challenges, methodological challenges, and information accessibility are hindrances to BIM application. They add that the specifications of data management systems must account for access to data, and provide efficient large datasets and comment that the building industry is behind in its application of information technology such as BIM and other data collection platforms [54].

Beazley et al. in [55] concluded that current problems in enhancing the energy efficiency of residential buildings could be reduced by better-informed design decisions and improved continuity of project data throughout project phases. They add factors such as industry resistance to innovation and technical limitations as barriers to increasing the application of BIM. The need to have new and more responsive workflows between project teams and also within them should be seen as an important requirement [55].

Sanhudo et al. reviewed BIM tools and software in energy retrofitting and introduced Revit as the computer software with the most potential for modeling the energy profile of a building [56]. They examined the architecture, engineering, and construction industry’s (AEC) research topics such as planning, structural design, and facility management and the recent development in the energy efficiency of buildings. The results of their investigation identified major issues throughout the BIM process in respect of building energy modeling (BEM) [56].

Furthermore, some studies have explored the factors and strategies contributing to the overall energy consumption of buildings. Najjar et al. [57] investigated the application of BIM in life cycle assessment and simulated several material combinations and mathematical equations to calculate the amount of energy saving during the project life. The researchers noted that building envelopes in exterior walls and windows have a profound role in energy assessment and energy cost estimation. In the case study Najjar et al. used, the impacts in terms of annual energy intensity were enhanced by about 45%, life cycle energy use and cost grew by more than 50%, and environmental impacts by more than 30%. Although this study shows a significant reduction in energy use, the limited number of parameters used in the research cannot be representative of the whole building [57].

Ranjbar et al. [58] investigated the environmental impacts of main structural members such as structural steel (SS) and reinforced concrete (RC) frames. They mention that in terms of material, there is a potential opportunity to enhance the energy performance of buildings. Embodied and operational energy is calculated by DesignBuilder, a computer software employed to analyze the energy consumption of buildings. The results show that SS-framed buildings have more destructive impacts on the environment, owing to greater energy consumption for the production process and more energy waste during the operational period. Although DesignBuilder is a simple and precise software for calculating energy consumption, the limitation of the variables and lack of integration between the various construction stages among designers is a drawback. This problem can be solved by using BIM platforms. Indeed, analyzers such as DesingBuilder can be partially used in different stages of modeling through BIM platforms [58].

Amani and Kiaee [59] ranked thermal insulation materials in nearly zero energy buildings using a multi-objective optimization approach. With a multi-story building case study, they probed the energy consumption of buildings and showed the amount of energy the building consumes by altering insulation materials .

Alla et al. explored in [60] the influence of several factors such as retrofitting, insulation, carbon payback period, and location, on building energy efficiency. The payback is based on the comparison between the saved operational energy stemming from the embodied energy of the insulation materials. The researchers declared that the climate is a critical variable when it comes to energy efficiency, especially when insulation systems play a role. In some countries like Italy, insulating the building members is mandatory and in cold cities, the payback period would logically be shorter. They conclude that retrofitting an existing building is more cost-effective than investing in new construction since embodied energy is a much higher proportion of total energy compared with operational energy [60].

Yu et al. investigated the effects of lighting systems on the overall consumption of electricity [61]. Since lighting systems consume much electricity, the peak demand for energy in buildings is influenced by this parameter. Yu et al’s research proposes a methodology to quantify the flexibility indicators for lighting system adjustments according to grid requirements. They calculate the seasonal differences in lighting demand with the application of lighting and occupancy control systems, the results showing that the average lighting power curtailment can be 32.6% of peak lighting [61].

Foteinaki et al. demonstrated in [62] the effect of heating systems on peak load and energy consumption. They investigated the potential for low-energy residential buildings to be operated flexibly, according to the needs of the district heating system. Thermal mass as passive energy storage can reduce the peak load by changing the maximum energy demand during the day. According to this research, during the morning peak, consumption can be reduced by 40% to 87%

when heat production is less expensive. They conclude that intelligent controlling systems can be a solution for satisfying the thermal comfort of occupants together with enhancing the energy efficiency of buildings [62].

Himeur et al. investigated the efficacy of energy control systems on energy savings [61]. Occupancy control systems such as motion detection, the Internet of Things, and ambient conditions controllers can reduce energy consumption through computer algorithms and information fusion strategies. These strategies can help reduce energy consumption by lowering the need for continual human control of energy consuming appliances [63].

As can be seen, whereas many parameters that affect the energy consumption of buildings have been investigated, a thorough and integrated study of the essential parameters for the energy management of buildings has not been conducted. In addition, the previous research outlined in the above paragraphs does not show an all-embracing view of the other important parts of the environment, such as trees, together with the building envelope, in an integrated model. The novelty of the research in this paper is having a holistic view of all parameters responsible for increasing the energy consumption of buildings in an integrated BIM model.

3. Research methodology

The research methodology of the current study includes three main stages. The first stage was associated with the identification of energy consumption optimization strategies in the building industry. To do so, an extensive study was conducted using secondary data from the existing literature such as journal papers, documents, books, online resources, and primary data by holding interviews with experts. It was followed by the second stage, which was weighing the identified strategies from the previous stage. A questionnaire was designed and distributed among energy experts and the results were gathered and analyzed using the SWARA method. Finally, strategies with higher weights were analyzed in a BIM simulation to assess their impact on energy consumption optimization in the last stage. A case study building in Shiraz, Iran, was simulated using BIM software, and the effect of each strategy was obtained. The research methodology is illustrated in Figure 1.

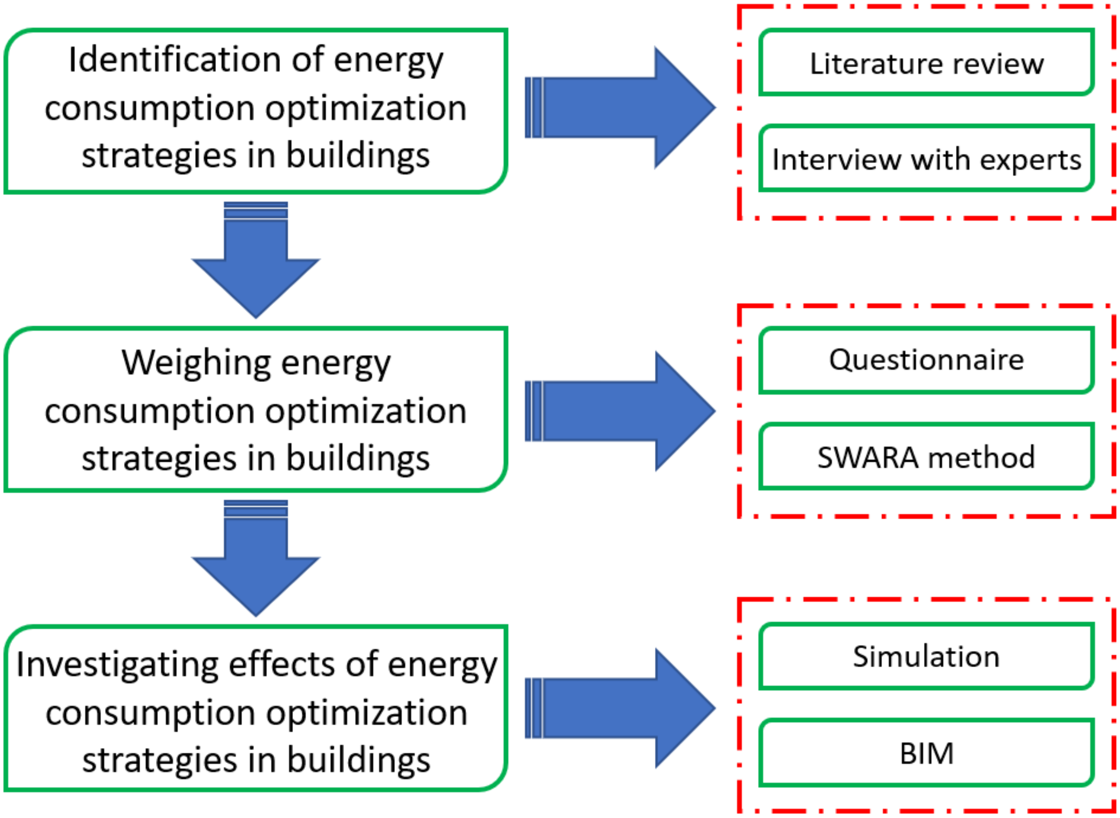

Figure 1. Research methodology.

3.1. Identification of strategies

Questionnaires are considered one of the most valuable means of gathering experts' opinions. Previous studies have exploited interviews and questionnaires to investigate or prioritize the variables in the AEC industry. Hosseini et al. studied the barriers to BIM application by ranking the reasons contributing to the disuse of BIM in construction projects based on a questionnaire survey [52]. Ranjbar et al. used interviews for narrowing down the sustainability criteria in green buildings, and questionnaires to prioritize the criteria for evaluating the environmental impacts of main structural frames [58]. Liu et al. used a questionnaire survey to define the key factors that would permit the AEC industry to minimize construction waste. The researchers then followed up by interviewing the top 100 architectural practices in the United Kingdom with the help of BIM [64]. Gerrish et al. utilized interviews with designers and operators to identify associated behavioral and methodological challenges in using BIM in building energy performance management [54].

The first step in the strategy identification was to identify energy consumption optimization strategies in buildings. To do so, a thorough investigation was conducted through the existing literature including journal papers, books, documents, and online resources. Also, 20 experts with more than 15 years of experience in both academia and the building energy field were interviewed to add any missing strategies. They were also asked if any item should be completely removed from the strategies as long as they did not apply to the main problem of the research. This stage was followed by categorizing the identified energy consumption optimization strategies according to their nature and expert suggestions.

In the current study, six types of questionnaires were designed and distributed among energy experts to weigh different categorizations of energy consumption optimization strategies and rank strategies in their specific groups. Experts were asked to rank the strategies using a 5-point Likert scale, in which one stands for the least effective and five stands for the most effective strategy.

In this stage, energy consumption optimization strategies were weighed and ranked. To do so, data collection was conducted through other types of questionnaires. Questionnaire type A was designed to prioritize different categories of energy consumption optimization strategies (G1-G5). Then, questionnaire types B-F were designed to rank energy consumption optimization strategies in their specific groups. All the questionnaires were designed and distributed among experts, and finally analyzed using the SWARA method.

The reliability of a questionnaire is crucial in research and the Cronbach's alpha test was used to check the reliability of these questionnaires. Cronbach's alpha coefficient value ranges between 0 and 1, and values higher than 0.7 are considered acceptable values [65]–[67]. The initially designed questionnaires were first distributed among 20 energy experts to check their reliability. After gathering the data, the coefficient value was calculated using SPSS software. Obtained results illustrated that Cronbach's alpha coefficient values of the questionnaires were more than 0.9 in all the questionnaire types, proving the reliability of the instruments. Table 1 illustrates the result of Cronbach's alpha test.

Table 1. Cronbach's alpha values of different questionnaire types.

Questionnaire Type	**Purpose**	**value**
A	Obtaining weights of energy optimization strategy groups	0.961
B	Obtaining weights of energy consumption optimization strategies in the "Technical Equipment (G4)" group	0.932
C	Obtaining weights of energy consumption optimization strategies in the "Construction Specification (G3)" group	0.981
D	Obtaining weights of energy consumption optimization strategies in the "Architectural Design (G1)" group	0.975

E	Obtaining weights of energy consumption optimization strategies in the “Law and Environment (G5)” group	0.956
F	Obtaining weights of energy consumption optimization strategies in the “Behavior and Operation (G2)” group	0.977

3.2. Sample size

Experts who were involved in building energy projects in Shiraz, in both industry and academia, were judged to be a valid sample size for this study. One of the most important points in using questionnaires is to calculate the required number of experts needed for filling the questionnaires out. In this case the number was calculated as follows [68]:

$$SS = \frac{z^2 p(1-p)}{c^2} \tag{1}$$

SS, z, p and c stand for the calculated sample size, the confidence level value, the percentage making a choice, and the confidence interval, respectively. The corrected sample size was according to the following formula:

$$Corrected\ SS = \frac{SS}{1 + (\frac{SS-1}{pop})} \tag{2}$$

Here "pop" stands for the population. Corrected SS for the response rate was then calculated "according to the following formula:

$$Corrected\ SS\ for\ rr = rr * corrected\ SS \tag{3}$$

while *“rr”* stands for response rate.

In the current study, 560 experts knowledgeable about energy optimization in buildings were identified. To get a suitable result, $p, z, c,$ and rr were considered 0.5, 0.95, 0.1, and 0.92, respectively. The final calculation illustrated that at least 490 experts were required to give their opinions. To ensure precise results, this study selected 500 experts. It is universally accepted that more experienced experts usually express more accurate scores. Therefore, experts with an experience of more than 15 years in the industry formed the majority of respondents. General information regarding experts is illustrated in Table 2.

Table 2. General information regarding experts.

Category	Classification	Number
Occupation	Architectural designer	161
	Project manager	101
	Contractor	68
	Supervisor engineer	60
	Consultant engineer	41
	Technical expert	38
	Structural engineer	31
Sex	Male	411
	Female	89
Experience (years)	<5	40
	5-10	60
	10-15	90
	>15	310

3.3. The SWARA method

The SWARA method was first introduced by Keršuliene et al. [12], [69], [70]. This method is regarded as one of the most accurate MCDM methods [71], [72]. According to Alinezhad and Khalili, It is known for evaluating attributes in which the experts' opinions are preferred in the first stage. This method can be used in combination with other methods as an advantage of this technique. Therefore, SWARA is considered one of the most widely used of the MADM methods [73]. Since the SWARA method involves simple calculations, the possibility of mathematical errors occurring would be minor. The results can also be checked by hand calculations, which is an advantage of numeric methods. Other MCDM methods such as COmplex PRoportional Assessment (COPRAS), analytic network process (ANP), and analytic hierarchy process (AHP) need a two-by-two comparison or matrix, which makes hands-on checking of the results more difficult. With the present research, the large number of energy optimization strategies led the research toward the use of the SWARA method.

The SWARA method is employed in many studies related to energy in buildings. For instance, Balali et al. weighted different criteria for selecting the best passive energy consumption optimization strategy using the SWARA method [12]. Ruzgys et al. applied the method to evaluate external wall insulation in residential buildings [74]. Ighravwe and Oke used the SWARA method as a part of their study for selecting a suitable maintenance strategy for public buildings according to sustainability criteria [75].

In the current research, the SWARA method was used to weigh and rank the identified energy consumption optimization strategies in buildings. To do so, a questionnaire was designed and distributed among experts. Respondents ranked the identified strategies using a 5-point Likert scale, in which 1 and 5 stood for the minimum and maximum impact on energy saving. The results obtained were then analyzed using the SWARA method. The procedure for applying the SWARA method is explained below [70], [73], [76]–[80]:

1. Identification of energy consumption optimization strategies in buildings.
2. Sorting the identified strategies in terms of relative importance in descending order according to the expert respondents' answers.
3. Calculation of comparative average value (s_j) by comparing the second important ($j-1$) criterion to the first criterion (j).
4. Calculation of coefficient k_j, which stands for comparative importance, as follows:

$$k_j = \begin{cases} 1 & j = 1 \\ s_j + 1 & j > 1 \end{cases} \tag{4}$$

5. Determination of recalculated weights (q_j):

$$q_j = \begin{cases} 1 & j = 1 \\ \frac{q_{j-1}}{k_j} & j > 1 \end{cases} \tag{5}$$

6. Calculation of the relative weights of the strategies w_j as follows:

$$w_j = \frac{q_j}{\sum_{m=1}^{n} q_m} \tag{6}$$

Where n stands for the number of energy consumption optimization strategies.

3.4. Building Information modeling

After obtaining the weights of the identified energy consumption optimization strategies in each group, the most important strategies were selected for further investigation. A building was simulated as a case study, and the effects of each selected optimization strategy were accurately calculated. To do so, two BIM tools, including Revit and Green Building Studio, were applied. Results obtained from this stage clearly illustrated how much the strategies could help reduce energy consumption in buildings.

The next stage of this study investigated the amount of energy saving for the identified energy consumption optimization strategies. To do so, the top strategies in each of the mentioned groups (G1-G5) were selected. To be more specific, for the top three groups (G4, G3, G1), the most two important strategies were simulated using BIM software. Also, for the last two groups (G3, G2), only the top strategy was selected and simulated. To conduct the simulation, various types of BIM software were used as illustrated in Table 3.

Table 3. Usage of BIM tools in different stages of the simulation.

Stage	**BIM software**
An initial draft of the building	Autodesk AutoCAD
3D modeling of the initial idea	Autodesk Revit
Material specification insertion	Autodesk Revit
Modeling HVAC system	Autodesk Revit
Energy conceptual and analytical design	Autodesk Revit
Energy analytical calculation	Green Building Studio
Annual energy consumption comparison	Insight 360

The building model was a 165 m^2 unit including a living room, a kitchen, a bathroom, and two living rooms. According to the Ministry of Housing and Urbanization, most buildings in this region were between 160 and 170 m^2. As mentioned above, one of the main characteristics of using the BIM methodology is having an integrated 3D model with comprehensive details available, if needed. The 3D model of the building simulated is shown in Figure 2.

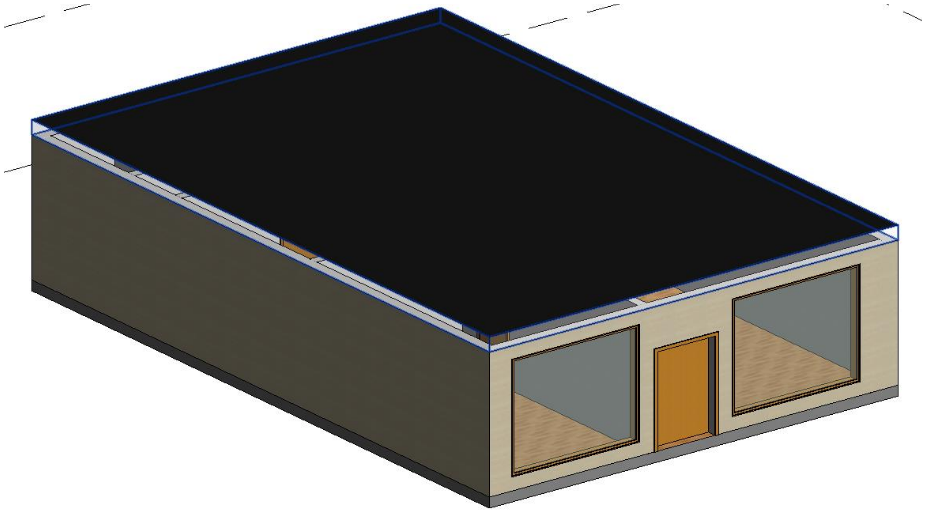

Figure 2. The 3D model of the case study building.

The analytical model is a representation of the physical model consisting of geometry, material properties, and building elements. The main parts of the analytical model were the living room, bathroom, restroom, and two bedrooms. The analytical energy model is shown in Figure 3.

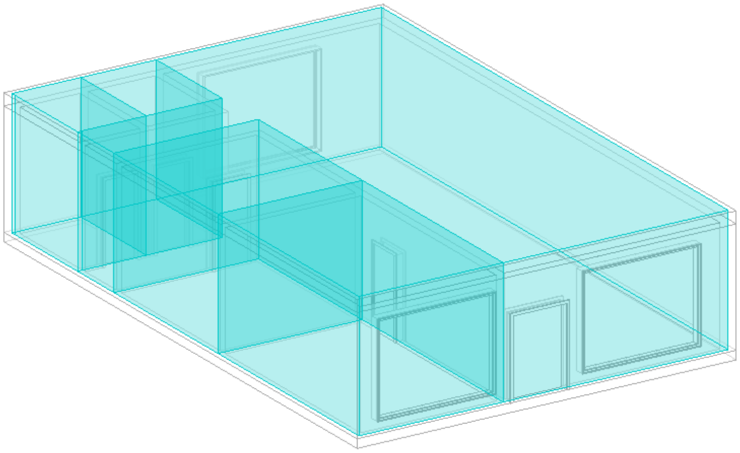

Figure 3. Analytical model of the case study building.

The case study building consisted of many parts including walls, windows, floor materials, doors, and the roof. Architectural parts of the building modeled are shown in Figure 4.

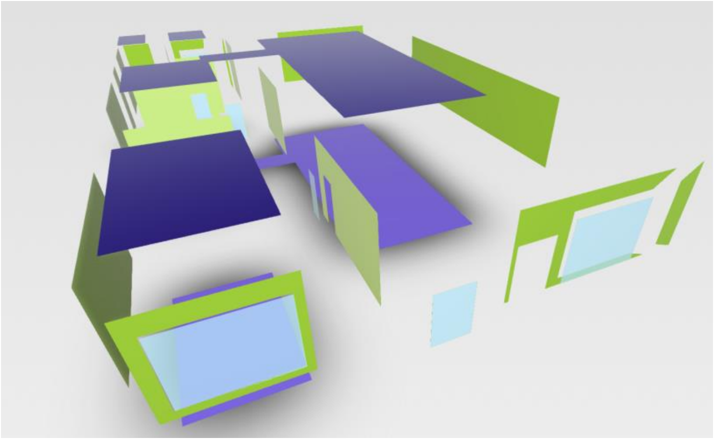

Figure 4. The members of the case study building model.

The details of the elements are shown in Tables 4 to 6. These tables show the specifications of the materials used in the model. Parameter “d” shows the thickness of the material, “λ” is the thermal conductivity, and “R” is the thermal resistance. Thermal conductivity is related to the material’s structure, but in thermal resistance, the numbers reflect the thickness of the material. As is seen, the clay blocks are the main structural part of the roofs, floors, and walls. To investigate the role of materials in the energy efficiency of buildings, the main part of each member such as the clay block system can be altered to calculate the energy consumption of the whole building.

Table 4. Roof layers for modeling the roof.

Layer name	**d[m]**	**λ[w/m.K]**	**R[m^2.K/W]**
Asphalt	0.03	1.15	0.026
Waterproof membrane	0.01	0.23	0.043
Cement mortar	0.02	1.00	0.020
Pumice	0.05	0.25	0.200
Clay block system	0.20	-	0.260
Gypsum mortar	0.02	0.57	0.035
Air gap	0.0014	0.01	0.14

Table 5. floor layers for modeling the floors.

Layer name	**d[m]**	**λ[w/m.K]**	**R[m^2.K/W]**
Floor laminate	0.02	1.65	0.012
Cement mortar	0.02	1.00	0.020
Clay block system	0.20	-	0.260
Concrete paste	0.02	0.57	0.030
Air gap	0.0022	-	0.22

Table 6. Wall layers for modeling the walls.

Layer name	**d[m]**	**λ[w/m.K]**	**R[m^2.K/W]**
Gypsum mortar	0.03	0.57	0.053
Clay block	0.20	-	0.30
Cement mortar	0.02	1.00	0.02
Air gap	0.0017	0.01	0.17

4. Results

4.1. Identification and categorization of optimization strategies in buildings

As mentioned in the methodology section, the first step in identifying the strategies was gathering them from the literature. Sixty strategies were gathered in the first place and were edited by 20 experts via the interview. They were asked if any removal, addition, or merging was necessary among the identified strategies. Finally, 29 strategies were identified as essential for enhancing the energy efficiency of buildings. The same interviewees were asked to categorize the 29 strategies into groups according to their nature. The identified strategies, and also their categorizations are illustrated in Table 7.

Table 7. Energy consumption optimization strategies in buildings.

Sign	Measures	Category
P11	Designing buildings according to the optimum estimation of investment cost	Architectural Design (G1)
P12	Designing buildings according to the optimum estimation of human resources cost	
P13	Using passive cooling systems	
P14	Using proper glazing	
P15	Using passive heating systems	
P16	Considering the building orientation	
P17	Considering the building shape	
P21	Considering energy prices in bills	Behavior and Operation (G2)
P22	Considering occupant comfort	
P23	Using energy controlling systems	
P24	Considering the peak energy demand	
P25	Considering the usage of the building	
P26	Considering O&M of the building	
P31	Using suitable materials	Construction Specification (G3)
P32	Recycling materials	
P33	Suitable building retrofit	
P34	Using efficient shading devices	
P41	Using efficient cooling systems	Technical Equipment (G4)
P42	Improving the efficiency of appliances	
P43	Using suitable energy grids	
P44	Using efficient heating systems	
P45	Using efficient fenestration materials	
P46	Using efficient insulation materials	
P47	Using efficient lighting systems	

P48	Using suitable ventilation systems	
P51	Considering the climate in building design	Law and Environment (G5)
P52	Considering energy efficiency protocols	
P53	Using renewable energy resources	
P54	Designing a suitable green area	

4.2. Weighing energy consumption optimization strategies

According to the obtained results, the “Technical Equipment (G4)” group was the most important category among all the groups with a weight of 0.231. Also, in the strategies’ categorizations themselves, “Using efficient insulation materials (P46)”, “Using suitable materials (P31)”, “Considering the building orientation (P16)”, “Using renewable energy resources (P53)”, and “Using energy controlling systems (P23)” were the top strategies in “Technical Equipment (G4)”, “Construction Specification (G3)”, “Architectural Design (G1)”, “Law and Environment (G5)”, and “Behavior and Operation (G2)” categories, respectively. Information regarding the mentioned prioritizations is illustrated in Tables 8-13. In the discussion chapter, each table is evaluated extensively.

Table 8. Weights of energy consumption optimization strategies groups.

Group	S_j	$K_j = s_j + 1$	q_j	w_j	**Rank**
G4	---	1	1	0.231	1
G3	0.067	1.067	0.937	0.217	2
G1	0.031	1.031	0.909	0.210	3
G5	0.168	1.168	0.778	0.180	4
G2	0.132	1.132	0.687	0.159	5

Table 9. Weights of energy consumption optimization strategies in the “Technical Equipment (G4)” group.

Strategy	S_j	$K_j = s_j + 1$	q_j	w_j	**Rank**
P46	---	1	1	0.160	1
P47	0.031	1.031	0.970	0.156	2

P45	0.247	1.247	0.777	0.125	3
P48	0.016	1.016	0.765	0.123	4
P42	0.025	1.025	0.747	0.120	5
P41	0.054	1.054	0.708	0.114	6
P44	0.098	1.098	0.645	0.103	7
P43	0.077	1.077	0.599	0.096	8

Table 10. Weights of energy consumption optimization strategies in the “Construction Specification (G3)” group.

Strategy	S_j	$K_j = s_j + 1$	q_j	w_j	**Rank**
P31	---	1	1	0.318	1
P34	0.174	1.174	0.851	0.270	2
P32	0.243	1.243	0.685	0.218	3
P33	0.130	1.130	0.606	0.192	4

Table 11. Weights of energy consumption optimization strategies in the “Architectural Design (G1)” group.

Strategy	S_j	$K_j = s_j + 1$	q_j	w_j	**Rank**
P16	---	1	1	0.183	1
P14	0.050	1.050	0.952	0.175	2
P17	0.202	1.202	0.792	0.145	3
P15	0.097	1.097	0.722	0.132	4
P13	0.023	1.023	0.705	0.129	5
P11	0.100	1.100	0.641	0.117	6
P12	0.027	1.027	0.624	0.114	7

Table 12. Weights of energy consumption optimization strategies in the “Law and Environment (G5)” group.

Strategy	S_j	$K_j = s_j + 1$	q_j	w_j	**Rank**
P53	---	1	1	0.308	1

P51	0.225	1.225	0.816	0.251	2
P54	0.024	1.024	0.797	0.245	3
P52	0.269	1.269	0.628	0.193	4

Table 13. Weights of energy consumption optimization strategies in the “Behavior and Operation (G2)” group.

Strategy	S_j	$K_j = s_j + 1$	q_j	w_j	**Rank**
P23	---	1	1	0.202	1
P25	0.270	1.270	0.787	0.159	2
P21	0.047	1.047	0.751	0.151	3
P24	0.150	1.150	0.653	0.132	4
P22	0.073	1.073	0.609	0.123	5
P26	0.062	1.062	0.573	0.115	6

4.3. Investigating the effects of optimization strategies via BIM

4.3.1. Simulating the “Technical Equipment (G4)” energy consumption optimization group

In this group, the first and second ranks were “Using efficient Insulation materials (P46)” and “Using efficient lighting systems (P47)”, respectively. Regarding the former, the simulation was conducted through the information provided by the Iranian Construction Engineering Organization. According to the mentioned organization, the most efficient insulation materials in Iran are “rockwool”, “polystyrene”, and “polyurethane”. The thermal resistance of the insulation materials was gathered from the most well-known companies in the Iranian construction industry. Thermal details and the weighting of the materials were then inserted into BIM software precisely, and a simulation was conducted. According to the results, both “rockwool” and “polyurethane” can reduce energy consumption by approximately 35%. Details of simulating this strategy are illustrated in Figure 5.

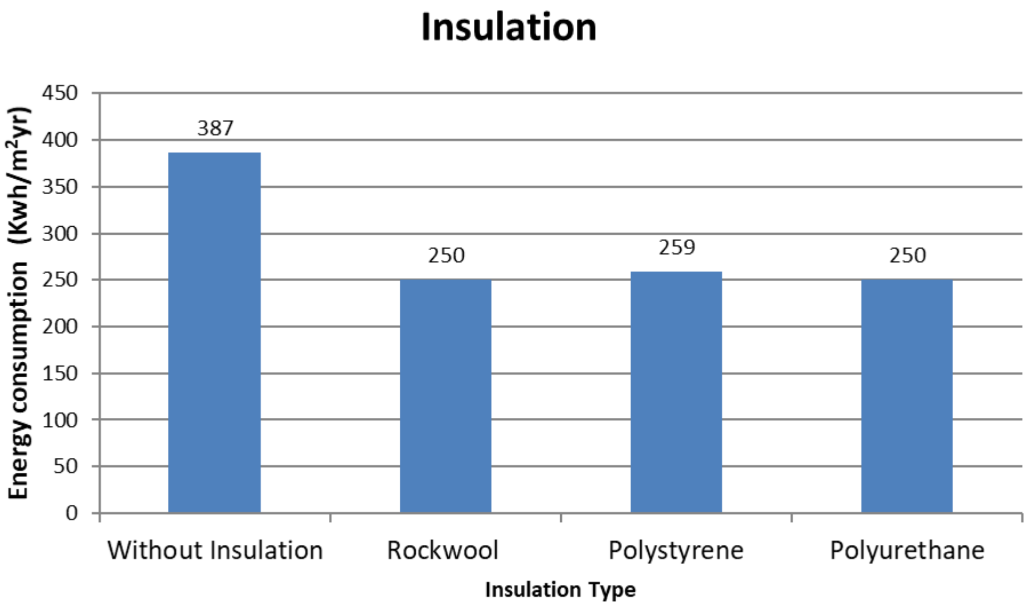

Figure 5. Simulation details for “Using efficient insulation materials (P46)”.

Regarding the latter, it is also known that lighting in buildings, as an active criterion, can have a profound influence on the energy consumption of the building, and therefore more efficient lighting systems have been designed in recent years. In this research, the lighting system has modeled and studied several efficient modern lighting systems. The energy consumption of the lighting system comprises 8 incandescent lamps with 200 watts consumption per lamp in the initial model and 10 watts per square meter. By changing the lighting system, the consumption of the building changed to 3.23 watts per square meter, using eight 65-watt light-emitting diodes. According to the results, the chosen lighting system can reduce energy consumption by about 10%. Details of simulating this strategy are illustrated in Figure 6.

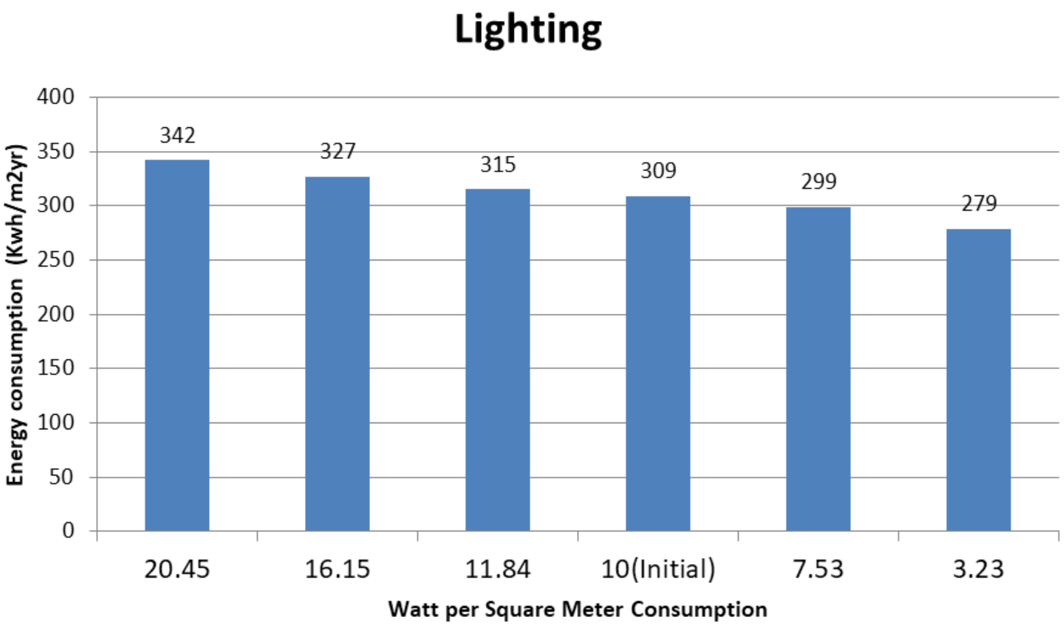

Figure 6. Simulation details of “Using efficient lighting systems (P47)”.

4.3.2. Simulating the “Construction Specification (G3)” energy consumption optimization group

The first and second ranks in this category were “Using Suitable Materials (P31)” and “Using Efficient Shading Devices (P34)”, respectively. Regarding the former, an inquiry was made to the Construction Engineering Organization to gather information on the most common materials used in Shiraz, Iran. “clay blocks”, “cement blocks” and “autoclave blocks” were the most common materials being used in roofs and walls and different composite walls were modeled in BIM using these materials. According to the results, “autoclave core composite wall” derives the maximum energy consumption reduction, which is approximately 23%. Details of the simulation are shown in Figure 7.

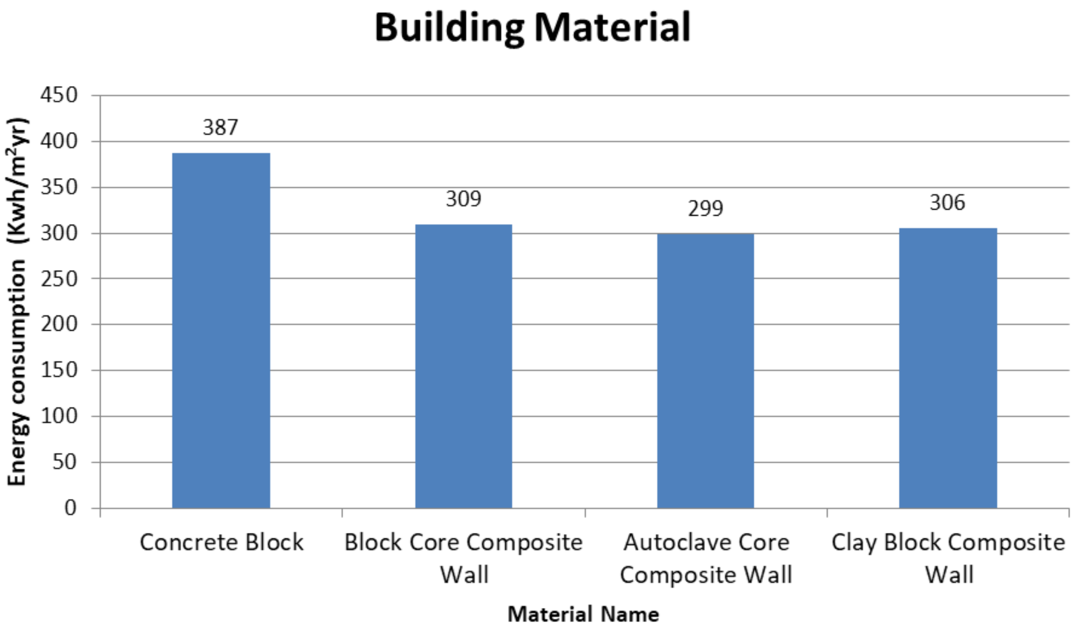

Figure 7. Simulation details of “Using Suitable Materials (P31)”.

As the second rank in this group was “Using Efficient Shading Devices (P34)”, the windows of the initial model, located at the south and north sides of the building, featured horizontal shadings. Then, the total energy consumption was calculated. In these calculations, the width of the shadings is a proportion of the window height. The results are shown in Figure 8 and Figure 9. It can be seen that if the shading length is half of the window height on the south elevation, the total energy consumption will be at a minimum (about a 1.13% reduction in energy consumption). However, since the solar gain is very low, shading for northern windows is not suggested.

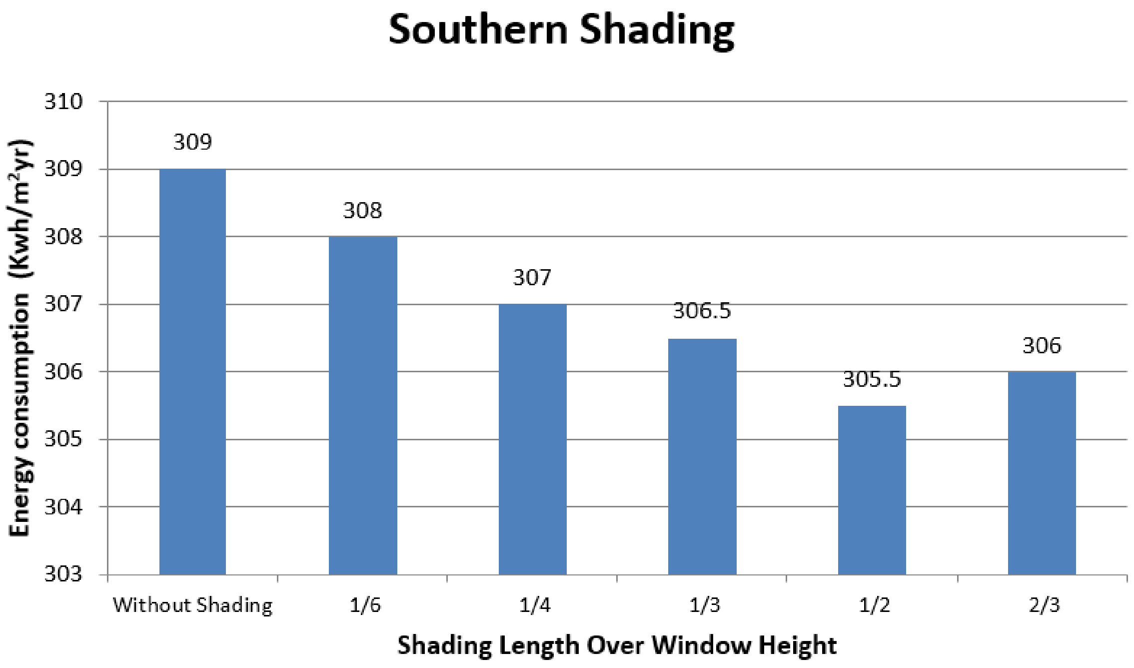

Figure 8. Simulation details of "Using Efficient Shading Devices (P34)", South.

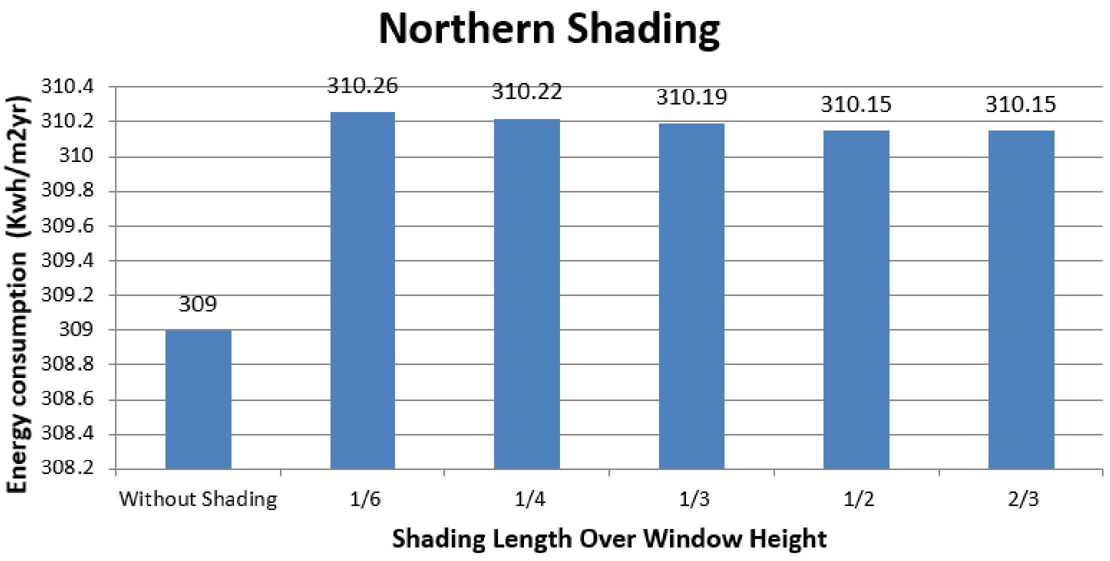

Figure 9. Simulation details of "Using Efficient Shading Devices (P34)", North.

4.3.3. Simulating the "Architectural Design (G1)" energy consumption optimization group

In this group, "Considering the Building Orientation (P16)" and "Using Proper Glazing (P14)" were the most important strategies. To identify the efficacy of building orientation in total energy consumption, the initial model was rotated 45 degrees clockwise. Accordingly, measures were taken to shape Figure 10, in which the total consumption of the building is depicted. As can be seen, 225 and 90 degrees of clockwise rotation reflect the least and the most consumption of energy, respectively.

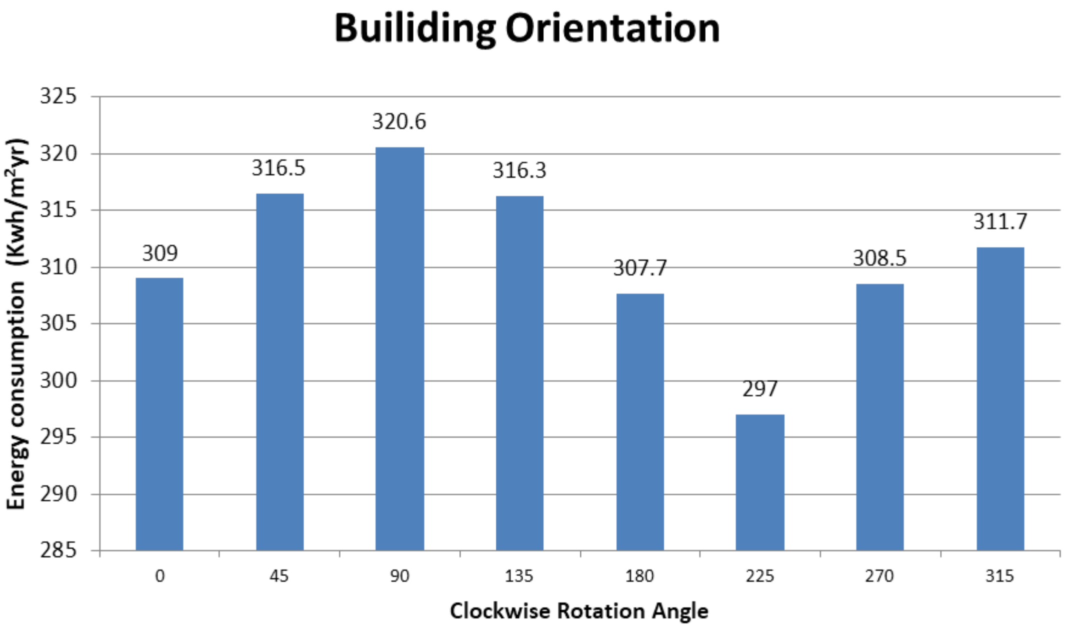

Figure 10. Simulation details of "Considering the Building Orientation (P16)".

As the latter strategy in this group was "Using Proper Glazing (P14)", the windows to wall ratios (WWRs) of glazing systems for all four exterior walls of the building were studied. The effects of various WWRs on energy consumption are shown in Figures 11 to 14.

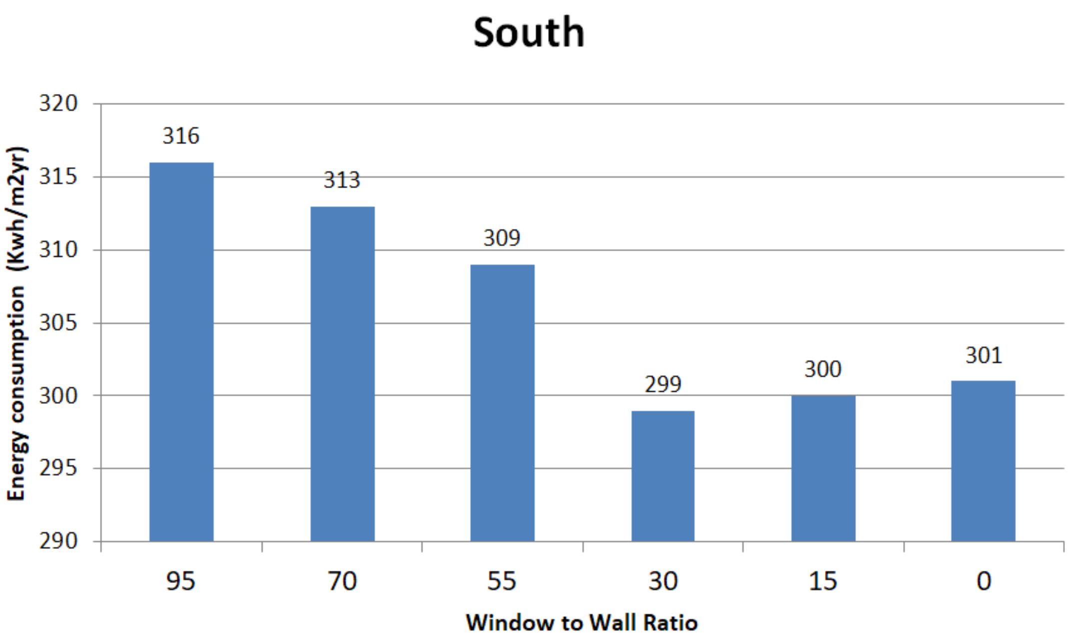

Figure 11. Simulation details of “Using Proper Glazing (P14)”, South.

According to Figure 11, the minimum energy consumption is 299 kWh with a glazing ratio of 30%, and the maximum energy consumption is 316 kWh with a glazing ratio of 95%. Technically, the glazing ratio in each country's building specification is limited by governmental codes and legal requirements. Glazing more than 95% of a wall is rare due to construction limitations. As seen, a 5% reduction in energy consumption (from 316 to 299 kWh) can be achieved by reducing the glazing in the south.

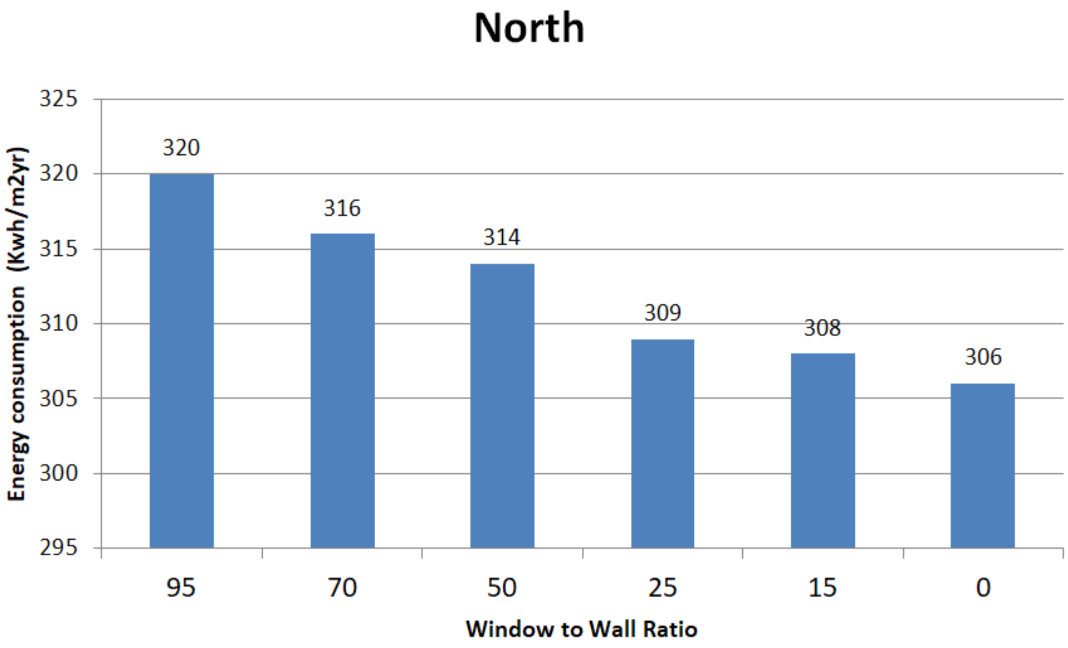

Figure 12. Simulation details of “Using Proper Glazing (P14)”, North.

Figure 12 shows that on the northern walls of the building, any windows can increase energy demand. Based on the location of the project and the hemisphere, the results may change, however. Reducing glazing from 95% to 0% obtains about a 4% energy reduction can be obtained (320 kWh to 306 kWh). Although minimizing windows on the north side is the best option for energy consumption, architectural design specifications and the benefits of natural light should be criteria in specifying the minimum size of windows.

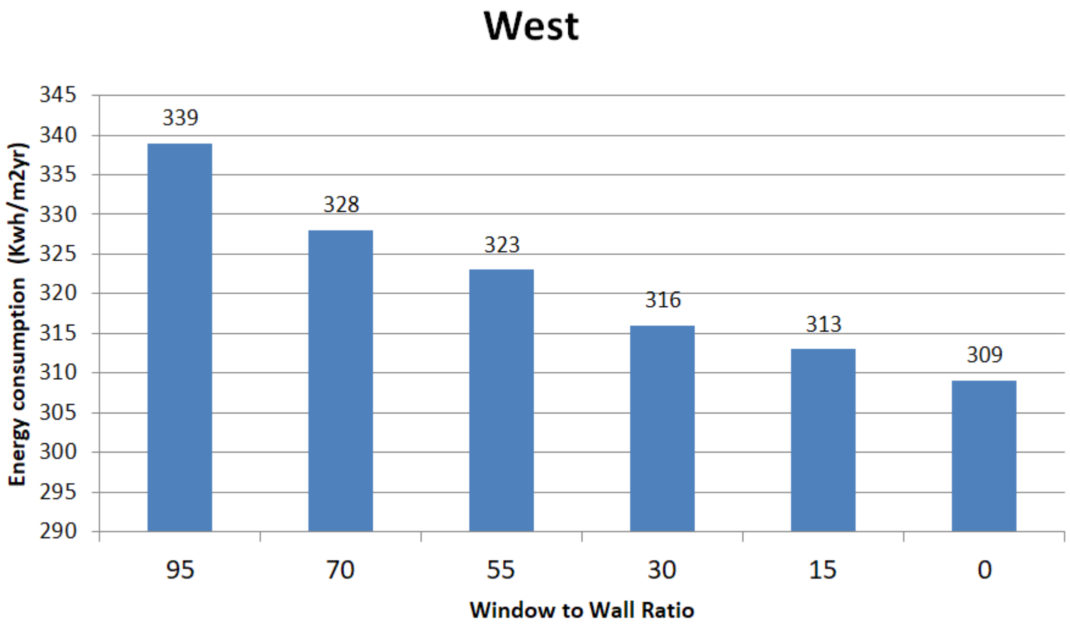

Figure 13. Simulation details of “Using Proper Glazing (P14)”, West.

The west side of the building is the most challenging one since direct sunlight during summer can increase the energy consumption during the year. Air conditioning systems should reduce the temperature to satisfy the thermal comfort limitations. According to Figure 13, reducing the window to wall ratio from 95% to 0% will achieve about a 9% energy reduction (339 kWh to 309 kWh). As mentioned before, architectural boundaries limit the minimum and maximum glazing, based on guidelines.

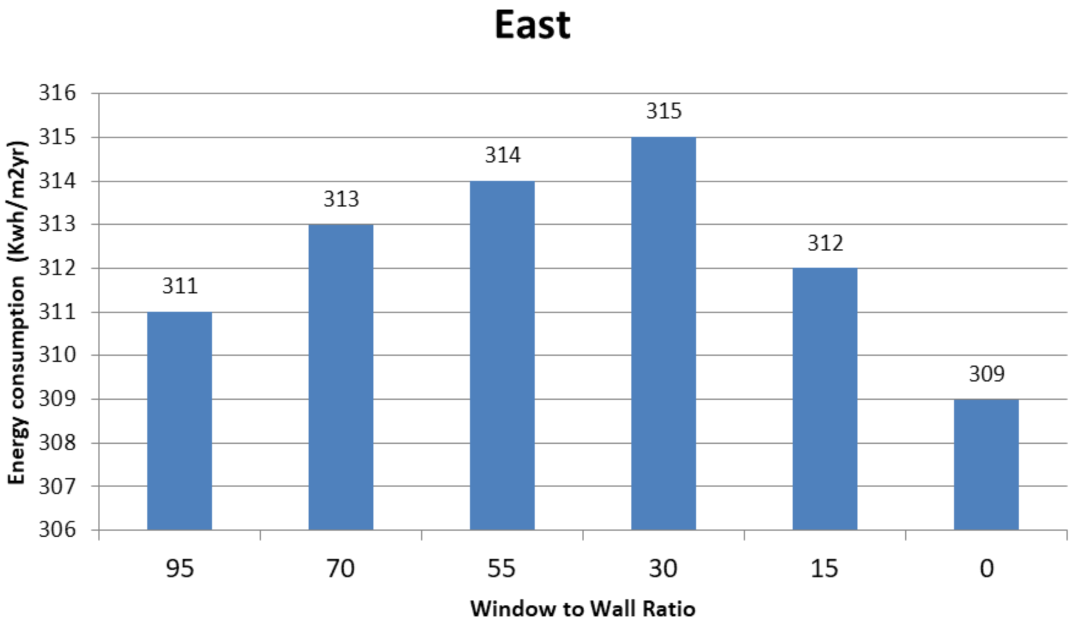

Figure 14. Simulation details of “Using Proper Glazing (P14)”, East.

As seen in Figure 14, the maximum energy consumption occurs with a 30% WWR (315 kWh) and the minimum is a ratio of 0% (309 kWh) which is around a 2% energy reduction. Depending on the climate and location, the easterly light is presumed to be suitable light for having more windows, but the results show it can bring more energy consumption.

4.3.4. Simulating the “Law and Environment (G5)” energy consumption optimization group

In this group of energy reduction strategies, the most important one was “Using Renewable Energy Resources (P53)”. This strategy, in contrast with others, is related to energy production, rather than an energy reduction strategy. In this regard, the total energy used from the grid was calculated and is shown in Figure 15. With an efficiency of 18% in photovoltaic panels, by covering 85% of the roof, the annual energy consumption of the building from the grid would be zero. This sustainability criterion is essential in achieving the architectural standards of NZE buildings.

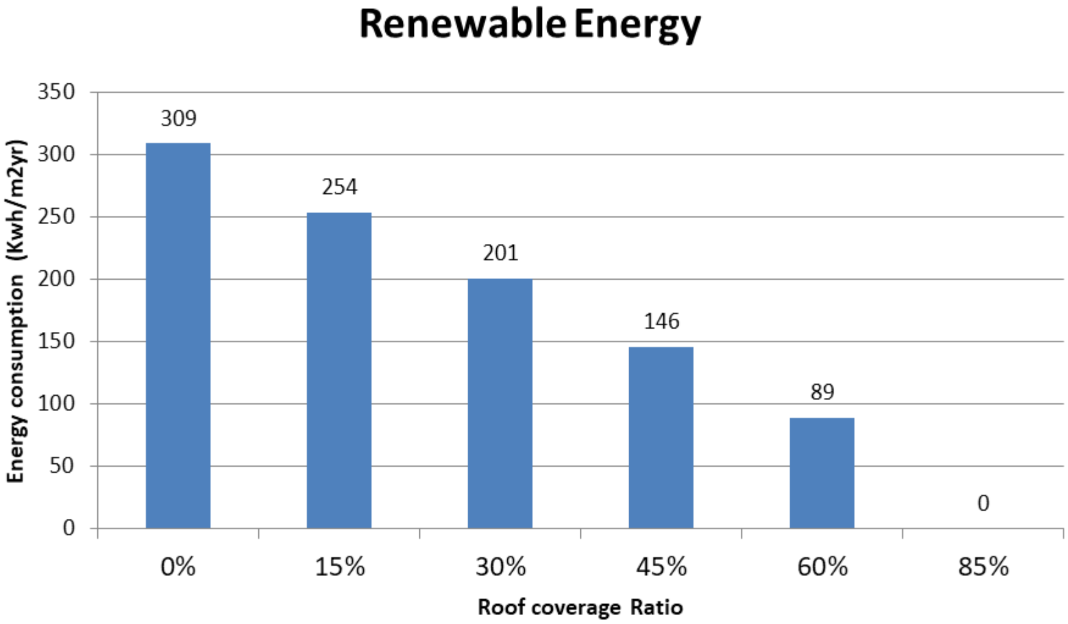

Figure 15. Simulation details of "Using Renewable Energy Resources (P53)".

4.3.5. Simulating the "Behavior and Operation (G2)" energy consumption optimization group

In this group, "Using Energy Controlling Systems (ECSs) (P23)" was identified as the most important strategy. The most common ECSs are "Occupancy Monitoring" and "Daylight Controlling Systems". With the utilization of sensors and a central processor, the energy-related behavior of the occupants can be monitored. Moreover, daylight control systems can analyze the amount of light needed for satisfying operational demands and these smart controllers can influence the total energy consumption of the building. Applying these systems will yield an energy reduction of about 2% of total consumption which is a satisfactory improvement for the level of investment needed. Details regarding the results of this simulation are illustrated in Figure 16.

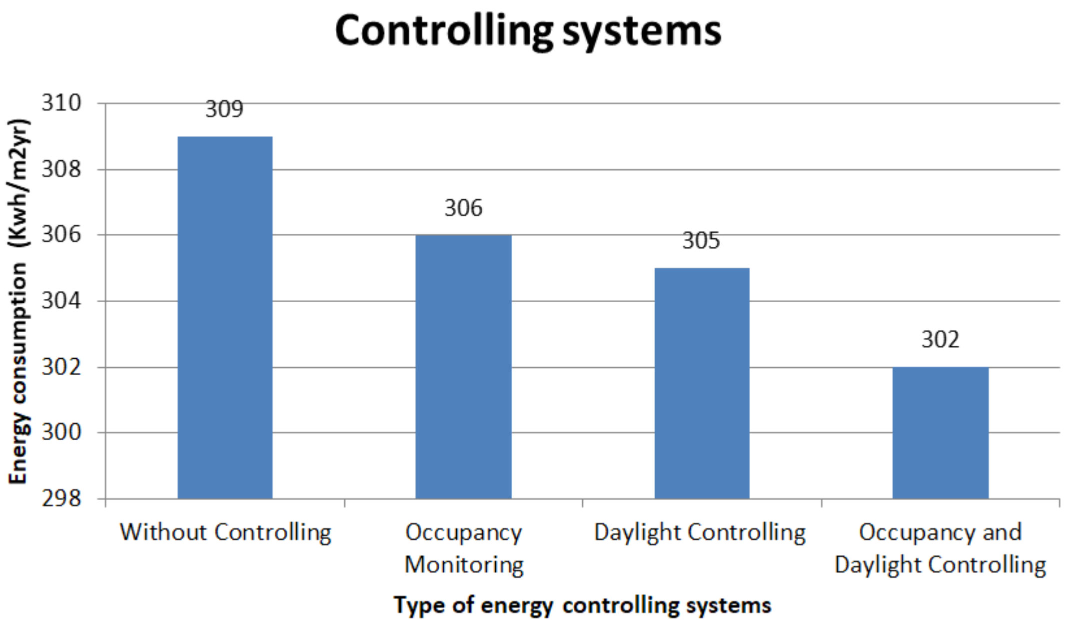

Figure 16. Simulation details of “Using Energy Controlling Systems (ECSs) (P23)”.

5. Discussion

5.1. Weighing optimization strategies

In Section 4.2 the tables show the weights of the identified strategies. In Table 8 the weights of the strategy groups are illustrated and Wj shows the relative weights of each group. The group of “Technical equipment (G4)” has a relative weight of 0.231 and consists of 8 strategies which are listed in Table 7. This group has the most significant relative weight compared with the next groups.

According to Table 9, “Using Efficient Insulation Materials (P46)” with a relative weight of 0.160 and “Using Efficient Lighting Systems (P47)” with a weight of 0.156 are the most important strategies in the designated group. The next one “Using Efficient Fenestration Materials (P45)” with a weight of 0.125 has a significant weight decrease in comparison with the second one.

In Table 10, “Using Suitable Materials (P31)” and “Using Efficient Shading Devices (P34)” have relative weights of 0.318 and 0.270 respectively. The following item with a weight of 0.218 is “Recycled Materials” which has a significantly lower weight in comparison with the second item.

According to Table 11, “Considering the Building Orientation (P16)” and “Using Proper Glazing (P14)” with weights of 0.183 and 0.175, respectively, are the most important strategies. The next strategy displays a significant weight gap and is “Considering the Building Shape (P17)”.

In Table 12, “Using Renewable Energy Resources (P53)” has the highest weight of 0.308. The second one, “Considering the Climate in Building Design (P51)” has a much lower weight in comparison with the first one.

In Table 13, “Using Energy Controlling Systems (ECSs) (P23)” with the weight of 0.202 is the most important strategy in the group “Behavior and Operation (G2)”. The second one has a much lower weight in comparison with the first one.

In groups G1 to G5, the difference in relative weights between strategies delineates the number of strategies to be checked by BIM simulations. It should be mentioned that the weights are specific to their groups, and they cannot be used to compare two different groups. For instance, the relative weight of P17 should not be compared with P51.

5.2. Ranking identified strategies according to BIM

To compare the efficacy of each optimization strategy, the total energy reduction achieved was compared with the initial energy consumption. “Using Renewable Energy Resources (P53)” was the most effective strategy to reduce the energy consumption from the power grid and able to convert the building to an NZE building. In second place was "Using efficient Insulation materials (P46)" with a 35% energy reduction. Complete details of the strategies are illustrated in Table 14.

Table 14. The rank of the identified strategies according to BIM

Rank	Sign	Effectiveness	Strategy Name
1	P53	100%	Using renewable energy resources
2	P46	35%	Using efficient insulation materials
3	P31	23%	Using suitable materials
4	P47	10%	Using efficient lighting systems
5	P14	4.2%	Using proper glazing
6	P16	4%	Considering the building orientation
7	P23	2%	Using energy controlling systems
8	P47	1%	Using efficient lighting systems

5.3. The U-Mann Whitney test

To double-check the reliability of the questionnaires, the perception of the respondents was analyzed with the Mann-Whitney test. The respondents were separated into two groups, one for academics and the second consisting of construction industry experts. The results are shown in Table 15. As can be seen, "Using Renewable Energy Resources (P53)" has an asymptotic significance of less than 0.05 which shows different perceptions among the experts. This stems from the concept of the energy-saving definition and the fact that renewable energies cannot reduce energy consumption, and only reduce the energy that would be supplied by the conventional energy grid. Although renewable energies have a profound effect on energy demand from coal or oil-fired power plants, using renewable energies cannot reduce the waste of energy in buildings [81].

Table 15. Results of U-Mann Whitney test.

Sign	Strategy	Asymp. Sig.
P11	Designing buildings according to the optimum estimation of investment cost	0.222
P12	Designing buildings according to the optimum estimation of human resources cost	0.474
P13	Using passive cooling systems	0.244
P14	Using proper glazing	0.240
P15	Using passive heating systems	0.492
P16	Considering the building orientation	0.432
P17	Considering the building shape	0.581
P21	Considering energy prices in bills	0.653
P22	Considering occupant comfort	0.418
P23	Using energy controlling systems	0.074
P24	Considering the peak of energy demand	0.062
P25	Considering the usage of the building	0.497
P26	Considering O&M of the building	0.589
P31	Using suitable materials	0.077
P32	Recycling materials	0.370
P33	Suitable building retrofit	0.251
P34	Using efficient shading devices	0.052
P41	Using efficient cooling systems	0.154
P42	Improving the efficiency of appliances	0.062
P43	Using suitable energy grids	0.192
P44	Using efficient heating systems	0.964
P45	Using efficient fenestration materials	0.533
P46	Using efficient insulation materials	0.164
P47	Using efficient lighting systems	0.750
P48	Using suitable ventilation systems	0.091
P51	Considering the climate in building design	0.068
P52	Considering energy efficiency protocols	0.561
P53	Using renewable energy resources	0.044
P54	Designing a suitable green area	0.470

5.4. Factor analysis test

The confirmatory factor analysis (CFA) is a statistical method to study the underlying factors which are affecting the results. [82]. To investigate the accuracy of the strategy categorization, the factor analysis method has been utilized in this study. To calculate the factor weights in each category, AMOS software was employed. Weights of the factors in the CFA method are shown in Table 16 and standardized values of more than 0.4 show the integration between the factors in each group. It can be seen that “Considering energy prices in bills (P21)” and “Considering Energy Efficiency Protocols (P52)” contain weights less than 0.4. For the former one, prices on bills are economic factors that can affect users' behavior. In the latter case, legal strategies are different from environmental strategies, so energy efficiency protocols are inherently different to the other three factors ("Considering the climate in building design (P51)", "Using renewable energy resources (P53)" and "Designing a suitable green area (P54)".

Table 16. Results of the factor analysis test.

Sign	Strategy	Standard Weight
P11	Designing buildings according to the optimum estimation of investment cost	0.47
P12	Designing buildings according to the optimum estimation of human resources cost	0.42
P13	Using passive cooling systems	0.54
P14	Using proper glazing	0.77
P15	Using passive heating systems	0.57
P16	Considering the building orientation	0.72
P17	Considering the building shape	0.69
P21	Considering energy prices in bills	0.37
P22	Considering occupant comfort	0.79
P23	Using energy controlling systems	0.69
P24	Considering the peak of energy demand	0.61
P25	Considering the usage of the building	0.75
P26	Considering O&M of the building	0.59
P31	Using suitable materials	0.68
P32	Recycling materials	0.62
P33	Suitable building retrofit	0.51
P34	Using efficient shading devices	0.43
P41	Using efficient cooling systems	0.82
P42	Improving the efficiency of appliances	0.87
P43	Using suitable energy grids	0.66
P44	Using efficient heating systems	0.53
P45	Using efficient fenestration materials	0.45
P46	Using efficient insulation materials	0.61
P47	Using efficient lighting systems	0.78
P48	Using suitable ventilation systems	0.86
P51	Considering the climate in building design	0.61
P52	Considering energy efficiency protocols	0.34
P53	Using renewable energy resources	0.65
P54	Designing a suitable green area	0.52

5.5. Other studies

Amani and Kiaee ranked thermal insulation systems, and with a single layer of 0.16 meters of mineral wool insulation, they achieved a 30% energy reduction. This result can validate the current study outcomes of gaining a 35% energy reduction by changing the insulation to the rock wool material [59]. Ranjbar et al. investigated the effect of main structural frames on operational energy and declared that RC-frame buildings are 2.3% more efficient than SS-frame buildings [58]. Marszal and Heiselberg note that a multi-story building can handle its own energy needs using renewable energy [83].

5.6. Limitations

Although sustainability criteria possess many similarities across different countries, some regional specifications can affect the results. Consequently, it is strongly recommended that location-related details be considered, such as the regional climate, local materials, accessible insulation systems, sunshine hours, humidity, and construction methods employed in the building's energy design. Moreover, the high number of factors in use was a limitation for performing a thorough investigation of all strategies in the building industry. However, as BIM methodology is highly flexible in its regional aspects, simply by changing the model settings such as location, material, occupational behavior, and weather conditions to the needed specification, the methodology and the results can be adapted to various applications.

A second limitation is that the analysis is a time-consuming process, even with computer software. Although cloud-based computations can boost the speed of building modeling, the sheer quantity of strategies was a limitation for a thorough analysis of all those collected through the survey work.

Analyzing the case study for all the strategies with high weight was another limitation. In this research, just one building with specific dimensions is analyzed and it may not apply to other buildings with different specifications.

6. Conclusion

Buildings are responsible for consuming a considerable amount of energy. In light of the dramatic energy consumption increase in the building and construction sector, a satisfactory solution must be found to reverse this trend. Therefore, in the current study, energy consumption optimization strategies were identified, prioritized, and the efficacy of the most important strategies for reducing the total energy consumption of the buildings was investigated. Initially, 29 strategies were identified and categorized into five groups including “Architectural Design (G1)”, “Behavior and Operation (G2)”, “Construction Specification (G3)”, “Technical Equipment (G4)” and “Law and Environment (G5)”. To prioritize the groups and strategies, the SWARA method was employed and the weights of the strategies were conducted. According to the results, G4, G3, and G1 were the most important categories. The most important strategies according to the SWARA method across the 5 groups were “Using efficient insulation materials (P46)”, “Using suitable materials (P31)”, “Considering the building orientation (P16)”, “Using renewable energy resources (P53), and “Using energy controlling systems (P23)”. Building Information modeling was employed to calculate the efficacy of the most important strategies in all 5 groups, “Using renewable energy resources (P53)”, “Using efficient insulation materials (P46)”, “Using suitable materials (P31)”, and “Using efficient lighting systems (P47)”. They gained 100%, 35%, 23%, and 10% efficacy, respectively, and were introduced as the major contributors to the energy consumption optimization.

The key contribution of this study is the procedure for gathering solutions which can reduce the energy consumption of buildings in quantitative terms with the efficacy of renewable energies in comparison with other strategies being clearly visible. The amount of energy that can be produced in a mid-size residential building is shown in the results and can be a model for new construction projects.

Insulation materials are one of the most important building elements, able to significantly reduce the amount of energy a building consumes during its lifecycle. The proper use of these materials, based on the location and the guidelines can help improve the energy efficiency of buildings.

The method used in this study can be employed in similar situations in the building industry. The results obtained in this study can be used in both Shiraz, Iran, and also cities having similar characteristics (such as humidity, annual clear days, and total sunshine hours) all around the world. Due to the high potential to save energy of the identified energy consumption optimization strategies, they have considerable potential to be used in the building industry generally as individual strategies or in combination.

For further research, it is strongly recommended that the remaining strategies be analyzed via BIM, and compared with the results from the current study. Other types of buildings with different shapes and sizes also should be investigated. Investments in new technologies connected with renewable energies and insulation materials can enhance the efficacy of energy reduction strategies. These fields can be an essential subject for future investigations.

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