Investigating the Environmental Impact of Reinforced-Concrete and Structural-Steel Frames on Sustainability Criteria in Green Buildings

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Abstract

Reducing the detrimental impact of human activities on our environment is an essential need. Buildings have a significant role in accomplishing this need, which necessitates the conduction of comprehensive research that adequately identifies the underlying factors and then seeks sustainable solutions. Green buildings have been one of the critical initiatives to lessen the negative impact of human endeavors on the environment. The structural frame is one of the most critical elements of buildings, especially owing to their impact on the environment. This study investigates how structural building frames perform according to sustainability criteria. A questionnaire was used to identify the relevant sustainability criteria, and a hybrid Delphi-SWARA model was used to determine the relative importance of eight comprehensive prioritized criteria. A building was simulated with DesignBuilder software to quantify the environmental impact of two main types of structural frames, reinforced concrete (RC) and structural steel (SS) frames, on sustainability criteria. Results illustrated that RC-framed buildings have a less detrimental impact on the environment due to less energy consumption and carbon emissions. The energy consumption in RC-framed buildings was 2.3% less in electricity consumption and 2.7 less in natural gas consumption. In addition, 88 tonnes of CO_2 emission can be reduced with this type of frame in a 50-year lifecycle which is more than 5% of the total CO_2 production of the building. The methodological approach used in this research introduces a novel way for decision-makers to consider the sustainability criteria in the design stage.

Keywords

Sustainability criteria; Reinforced concrete; Structural steel; Green buildings; Delphi model; SWARA method.

1. Introduction

Recently, global warming and the impact of human activities on the environment have been at the forefront of most international agendas, owing to the detrimental effects of such activities continue to exert across the globe. Many factors are identified as active contributors to this issue. The total energy supply (TES) has reached 14.2 Gigatonne of oil equivalent (Gtoe) globally, and more than 80 percent is produced by fossil fuels, mainly oil, coal, and natural gas [1]. Building construction and operation sectors are responsible for more than one-third of total energy consumption and approximately 40% of total CO_2 emissions [2]. CO_2 emission from electricity and commercial heating in buildings reached approximately 10 Gigatonne in 2019 [1]. Amidst the current enormous emission rates, rising global population, urbanization, and disproportionately large migration to urban areas [3] continue to heighten overall energy demand [4], [5]. Therefore, the correlation between current population growth rates, rapid depletion of conventional energy sources (3701 Mtoe in 1965–13511 Mtoe in 2017) [6], [7] and the environment has triggered a shift in research paradigm towards the investigation of sustainable building and construction mechanisms.

Green buildings and sustainable construction activities have been highly concentrated solutions for reducing Green House Gas (GHG) emissions and their detrimental effects. The application of approaches such as Lifecycle Assessment (LCA) [8], [9] helps the understanding of the harms caused by GHGs and also the effectiveness of remedial actions. Despite the variations in the standard definitions of “green buildings” and “sustainability,” both concepts are often employed in close association with each other and sometimes interchangeably. “Green” is a specific term and often focuses on products, people, and the environmental impact, while the “sustainable” term has a more encompassing definition that includes the environmental, social, and economic pillars of sustainable development [10], [11]. Therefore, any sustainable solution must be able to reduce the devastating consequences of human activities from the standpoints of all pillars (i.e., environmental, social, and economic), since studies [4], [12] have indicated that sustainable building and construction can reduce global warming and water pollution by more than 30%.

In order to adequately minimize the destructive ramifications of building construction, the identification of various sustainability factors that exist in building construction and operation is crucial. Embedding sustainability at the design stage of constructions, compared to retrofit stages, often offers immensely higher cost-saving opportunities, reliability, and safety throughout the asset lifecycle. Some techniques such as Lifecycle Assessment (LCA) and Building Information Modeling (BIM) are proven to help conduct a comprehensive assessment of the overall needs of construction projects, including safety hazards, sustainability criteria as well as the operations and maintenance needs throughout the lifecycle [13]–[19].

Several rating systems and research endeavors have aimed at probing into factors influencing the sustainability status of construction procedures. For instance, the Leadership in Energy and Environmental Design (LEED) rating system is a multi-criteria approach for assessing the sustainability of buildings, which adequately recognizes building site, water, material, atmosphere, air quality, and innovation measures, as factors that can easily sway the overall ranking of a building from a conventional to a green project [20]–[23]. The influence of internal air quality was investigated by Ullah et al.. It reaffirmed its criticality and correlation with the achievement of sustainability in buildings, mainly due to its impacts on other factors such as occupant comfort or exhaust systems reliability [24].

Other studies [25]–[30] have demonstrated that water management and sustainability are inextricable. This phenomenon may be why parameters such as water-related building codes, water price, wastewater reuse, leakage reduction, and effective desalination are gaining more significant influence as sustainability measures. Similarly, Huo et al. [31] investigated the highly critical components for designing green buildings. They indicated that environmental issues such as water pollution and effective use of space and resources are crucial, especially when incorporated at the design stage. Ospina et al. [32] also buttressed this point by studying the LEED certification based on water and energy consumption evaluation [32].

Energy and carbon design for zero energy communities has also been widely investigated by several researchers [33]–[35]. For instance, Balali et al. have studied the passive energy optimization measures in sustainable buildings [36], while Jie et al. investigated the impacts of wall and roof thicknesses on the calculation of energy consumption and pollutant emissions [37]. Brown et al. studied the greenhouse emissions from residential buildings and how such knowledge can support energy efficiency in buildings. Nizam et al. and Acampa et al. declared that embodied energy, transportation, and innovation associated with design processes are essential for standardizing the sustainability of building construction [16], [38]. Pham et al. stated that the incorporation of emerging and innovative technologies such as artificial intelligence and machine learning into building management activities could significantly enhance energy consumption [6], [39] which will, in turn, improve energy efficiency and reduce GHGs [40].

Various studies have reported construction and maintenance to exert a profound influence on achieving a sustainable society. For instance, these activities represented approximately 36% of global energy usage and 39% of total CO_2 released in 2017 [6], which makes the transition towards Net Zero-Energy buildings (NZEBs) or Zero-Emission buildings more imminent [41]. There are significant investigations into the amount of GHGs attributable to the building industry and its activities [42], [43]. To mention a few, Vares et al. investigated the significance of embodied and operational GHGs, after using a representative case study to estimate potential emission reductions in the context of NZEBs [43]. The study by Balasbaneh et al. demonstrated the efficacy of some structural walls on the management of GHGs [42], although few cases were considered.

The impact of alteration in building materials and structural elements on three pillars of sustainability has also been investigated by previous studies [10], [44], [45], including Balasbaneh et al. providing the environmental, economic, and social assessments of five types of hybrid timber structures in Malaysian low-income houses [46]. Rossi also explored the sustainability of stainless steel as a construction material [47]. Robati et al. investigated the influences of construction systems (mainly flat and waffle slabs) and structural materials (regular concrete and ultra-lightweight concrete) on the overall costs of a high-rise building [8]. Zhong and Wu examined the environmental and economic impacts of structural frames in Singapore, where it declared that the GHG in reinforced concrete (RC) buildings is 1.24 to 1.5 times more than that recorded in steel structure (SS) frames [48]. Peyroteo et al. declare the RC-framed buildings having far less embodied CO_2 and energy [49].

Quantitative and qualitative research methods are universally recognized as two of the most common and frequently applied ways for generating research data. Quantitative research helps to establish and validate correlations and generate outputs that enrich an existing theory [50]. Qualitative research, on the other hand, is an all-encompassing approach that entails discovery. It is also referred to as an unfolding model that often arises from natural settings, enhancing an in-depth understanding of the studied phenomenon [51]. Owing to the limitations associated with each of the mentioned methods, it has become quite common to adopt a combined strategy whereby the strengths of the qualitative technique compensate for the weaknesses of the quantitative technique and vice versa [51]–[55].

Although many studies have considered some of the factors that affect main sustainability pillars, very few have thoroughly quantified the sustainability criteria related to the main structural frames of green buildings.

The current study attempts to reduce some of the perceived uncertainties commonly attributed to quantitative estimation approaches. The study aims to identify the sustainability criteria for both RC-framed and SS-framed buildings at the first stage. Once the relevant sustainability criteria are identified, a specifically designed questionnaire was used to acquire relevant data, which were rationalized and ranked based on the outcomes of a hybrid Delphi-SWARA model to prioritize the mentioned criteria. In the third stage, a case study model in Shiraz, Iran, is simulated to calculate the energy consumption and CO_2 reduction in green buildings by replacing SS frames with RC frames. Besides using a hybrid approach that allows the technique's strengths to compensate for the weaknesses, the main novelty here involves incorporating a dynamic 3D modeling to show how main structural frames in green buildings impact the sustainability criteria.

2. Methodology

This section provides details regarding the particular approach employed to identify, extract, prepare, and analyze data about the phenomenon of interest, enabling readers to assess the reported outcomes' representativeness adequately. Owing to the multi-faceted adoption in this study, a description of the various tools and techniques applied is given in the following paragraphs to enhance clarity. The current study similarly adopts a combined or mixed research approach, whereby the qualitative element generates the contributing factors via observations, field research, and structured interviews. The quantitative element generates data via surveys, multivariate analysis, and simulations. This multi-faceted research approach was implemented in three main stages. In stage one, published sustainability factors were gathered through a comprehensive analysis of existing information through academic literature (journal articles, conference articles, book chapters), building codes, open-source data, and expert interviews. Stage two involved prioritizing all of the factors compiled in stage one using a Step-wise Weight Assessment Ratio Analysis (SWARA) method. Specifically designed questionnaires were submitted to building construction experts to deduce their opinion about the most important sustainability criteria to accomplish this stage. The third and final stage concerns the modeling of a representative case study to probe into the influences of each parameter on the entire building. The case study building is located in Shiraz, Iran, and it was simulated with EnergyPlus simulation engine [56], which is integrated within the DesignBuilder software [57], [58]. Figure 1 depicts the applied research methodology.

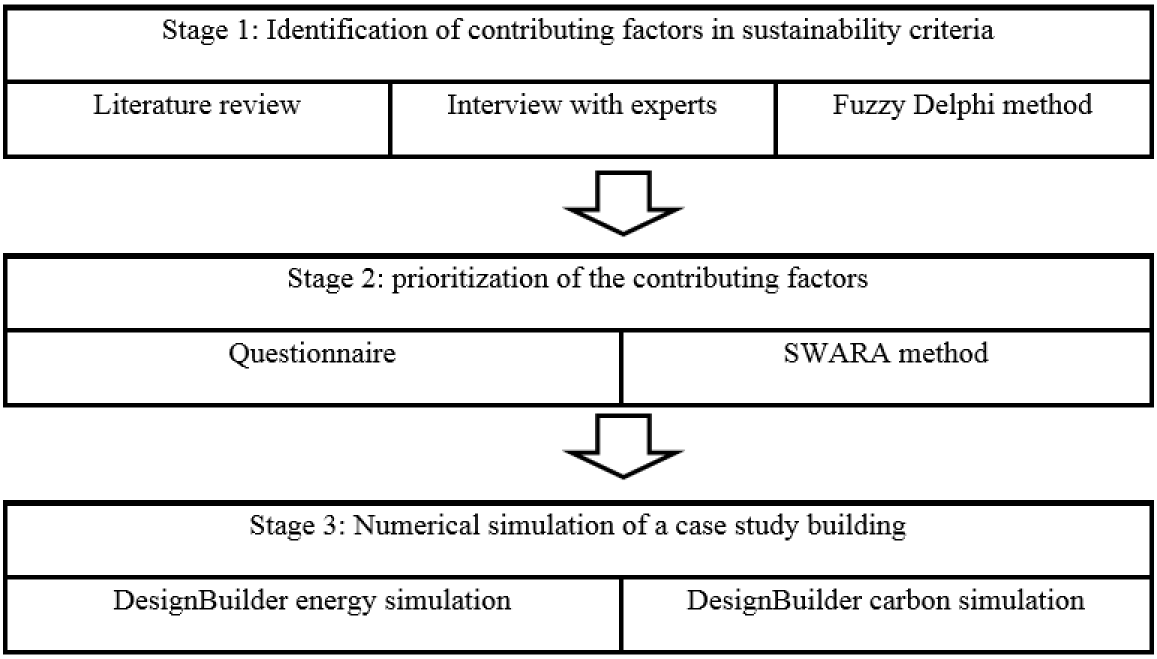

Figure 1: Research methodology

The initial quantity of the factors for identifying the sustainability criteria was 51, of which 41 were not directly related to the environmental impacts of the structural frames, and they were omitted (i.e., project schedule optimization and cost overruns). The omitted factors were among the sustainability criteria, but the direct influence of the structural frames on them in green buildings was denied for the experts in the interviews. The experts distinguished ten all-embracing criteria as the most effective to be analyzed in the following steps.

2.1 Identification of contributing factors in sustainability criteria

2.1.1 Selection criteria for literature review

The contributing sustainability factors were collected from the literature review to identify the environmental impacts of alteration in the main structural frames in green buildings. The Recent investigations on green buildings were gathered from 2010 to 2021 (the majority were from 2017 to 2021) by published papers.

2.1.2 Selection criteria for the experts

The representativeness of a study is partly determined by the quality and size of the sample. It is therefore imperative to estimate the minimum acceptable sample threshold. The sample for this study was drawn from a population of experts (industry and academic professionals) involved with building construction projects in Shiraz, Iran. The minimum number of experts (sample size) required to complete the questionnaires was determined based on Equation (1), where SS, z, p, and c respectively denote sample size, correspondent value of confidence level, interval, and selection percentage.

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

Equations (2)-(3) were used to generate a corrected sample size (SS), and rr denotes the response rate. :

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

In Equation (2), pop is the population and the corrected sample size (SS) for the response rate was estimated using the following formula while the rr is the response rate:

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

In this study, population was considered the number of experts in the current topic in Shiraz, Iran, which was 232 people. Although the estimations conducted with Equations (1)-

(3) indicated that a sample size of 63 respondents would be adequate, this study analyzed all of the 130 responses acquired from the participating experts. The values of p, z, c and rr considered for the computation of corrected SS are 0.5, 1.96, 0.1, and 0.8, respectively. Table 1 provides the general information about the participating experts for this study.

Table 1: General information regarding experts

Category	Classification	Number
Occupation	Structural engineer	26
	Project manager	36
	Contractor	12
	Environmental engineer	25
	Technical expert	13
	Architectural engineer	18
Sex	Male	101
	Female	29
Experience (years)	<5	15
	5-10	26
	10-15	36
	>15	53
Educational degree	P.h.d	26
	Master’s	51
	Bachelor’s	53

2.1.3 Delphi method

RAND Corporation developed the Delphi method in the 1950s, and it aims to create an approach that can enable the achievement of a coherent and reliable consensus of a group of experts[59]–[65]. Delphi is primarily used to structure a group communication process that allows experts to resolve complex phenomena collectively. According to notable studies [66], Delphi is most suitable when judgmental information is imminent, and typical inputs are a set of questionnaires strewed with controlled opinion feedback. A crucial characteristic of this approach is its ability to prevent direct confrontation between the participating experts [66]. Figures 2 and 3 depict the flowcharts that describe the general Delphi procedure for selecting experts and study administration [67] :

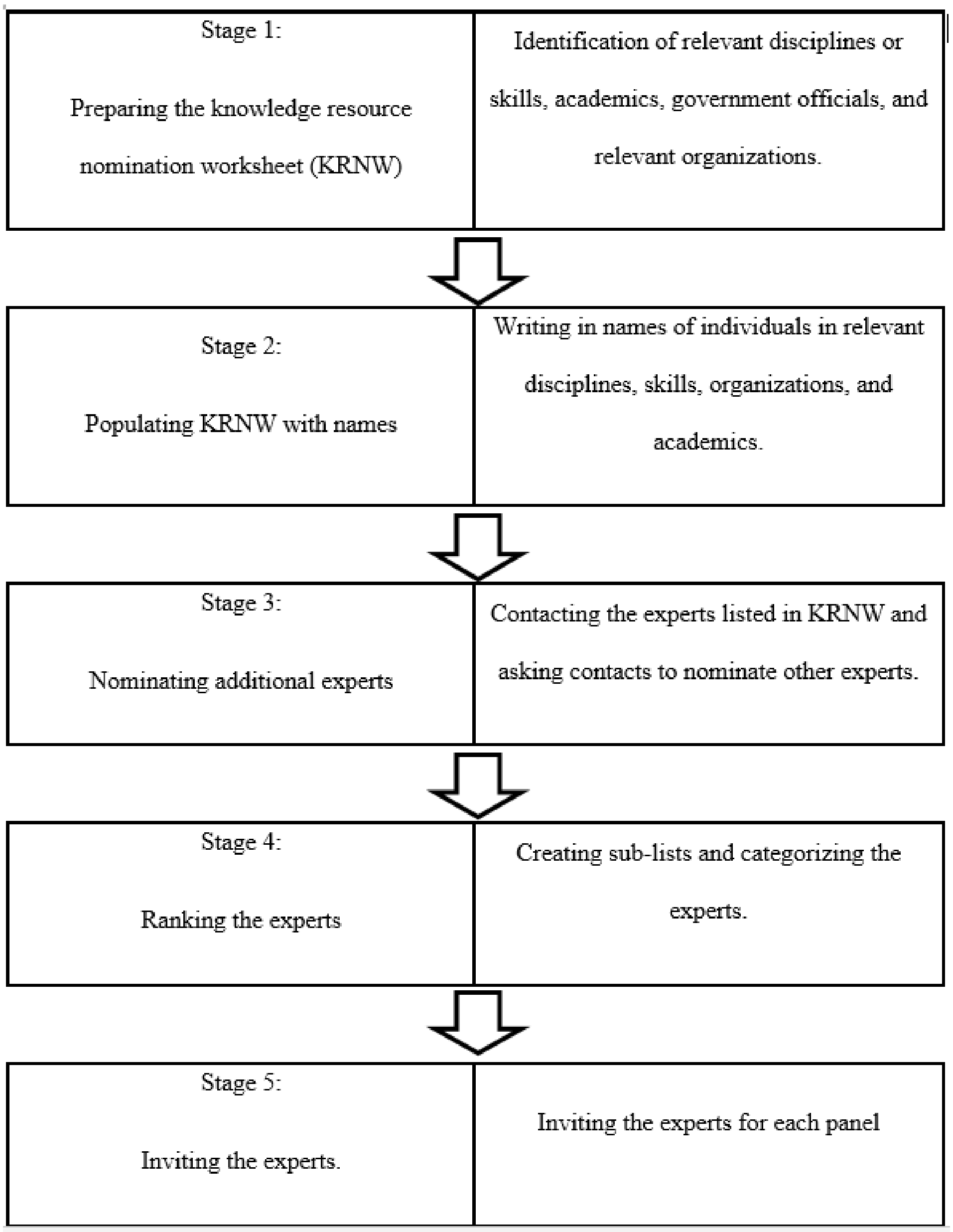

Figure 2: The expert selection procedure[67]

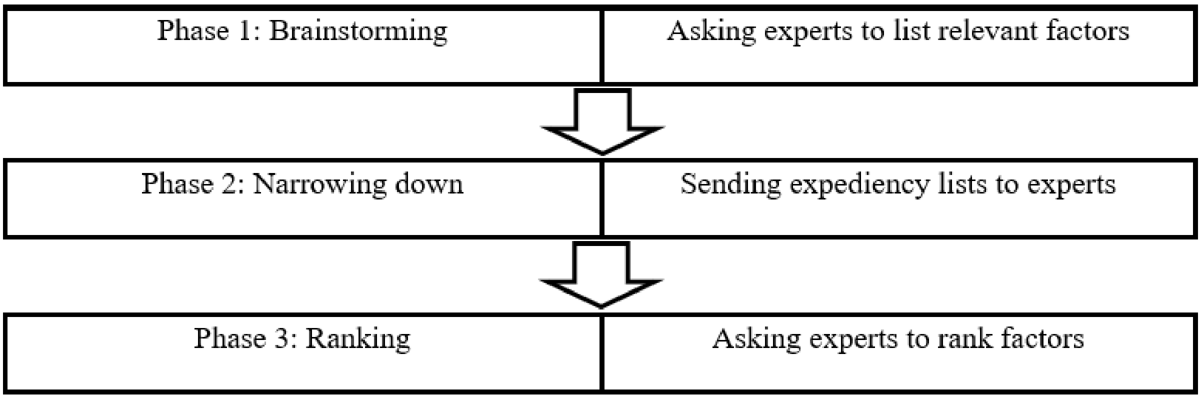

Figure 3: Delphi study administration[67]

2.2 Prioritization of contributing factors

2.2.1 Questionnaire

Questionnaires are systematically constructed questions directed at voluntary participants of a research study to generate statistically meaningful information about a phenomenon of interest. They must be adequately designed and responsibly administered [68]–[70]. The four main questionnaires used are open-ended, closed-ended, contingency, and matrix [70]. In this study, a combination of closed and open-ended questions was specifically designed.

The questionnaire was made up of three main sections and twelve questions. Section one of the questionnaire focused on general information of respondents, including their sex, occupational fields, levels of experience, and educational attainments. Section two contained the main questions needed to assess the factors that influence the sustainability criteria of green buildings, which would also serve as inputs to the Delphi analysis phase of the research. This section is comprised of eight questions, with each question assessing a critical sustainability criterion. The respondents were asked to rate the importance of each factor based on a 5-point Likert scale [10]. On the Likert scale, numbers 1, 2, 3, 4, 5 denoted not important, low importance, on average, important, and very important, respectively. In order to ascertain the reliability and internal consistency of the questionnaire, Cronbach's alpha coefficient was calculated using IBM SPSS software. Equation (4) depicts the underlying theory [71], [72]:

A specific quantity should be measured that is a sum of K items, where $\mathrm{X} = \mathrm{Y}_1 + \mathrm{Y}_2 + \cdots + \mathrm{Y}_\mathrm{K}$, then the Cronbach's α can be defined as follows:

$$\alpha = \frac{K}{K-1}\left(1 - \frac{\sum_{i=1}^{K}\sigma_{Y_i}^2}{\sigma_X^2}\right) \tag{4}$$

σ_X^2 and $\sigma_{Y_i}^2$ are the variances of the observed total scores, and item (i) is the current sample. Acceptable results for internal consistency are obtained when $\alpha > 0.7$. In this study, Cronbach's alpha coefficient was 0.79, suggesting that the items have an acceptable internal consistency

The third and final section offered the respondents the opportunity to provide free-text comments on any other critical sustainability factor they perceived as relevant but missing from Section 2 of the questionnaire.

2.2.2 SWARA Method

Step-wise Weight Assessment Ratio Analysis (SWARA) is a multiple criteria decision making (MCDM) method that is often considered advantageous for prioritizing results and observations by several researchers because of its simplicity, ease of implementation, speed, and not a requirement for binary comparisons [15], [36], [64], [73]–[78]. Moreover, The second stage of this research (prioritizing the identified criteria of the first stage) is entirely compatible with the application subjects of the SWARA method. As the questionnaires designed for the first stage have a specific importance number for each criterion, it could be the input for the SWARA method, and it reduces the time and effort to design, distribute, and collect another questionnaire.

In this study, the SWARA method is employed to assess the weight of each sustainability criterion. The inputs to the SWARA are the experts' responses to each criterion, while the outputs are the relative weights of each parameter, which in turn offers a means of ranking according to perceived importance. A typical SWARA method is implemented through the following stages [79]:

- Identification of the sustainability criteria in buildings.
- Sorting the identified criteria in terms of relative importance.
- Calculating the comparative average value (s_j) by comparing the second important $(j-1)$ criterion to the first one (j).
- Calculating the comparative importance coefficient (k_j) as depicted by Equation (5):

$$k_j = \begin{cases} 1 & j = 1 \\ s_j + 1 & j > 1 \end{cases} \tag{5}$$

- Determination of recalculated weights (q_j) as shown in Equation (6):

$$q_j = \begin{cases} 1 & j = 1 \\ \dfrac{q_{j-1}}{k_j} & j > 1 \end{cases} \tag{6}$$

- Calculation of relative weights of the strategies (w_j) as shown in Equation (7), where parameter n represents the quantity of the considered criteria:

$$w_j = \frac{q_j}{\sum_{m=1}^{n} q_m} \tag{7}$$

2.2.3 CVR Method

The Content Validity Ratio (CVR) is a well-known method to assess the validity of questionnaires [80]. Lawshe first introduced it in 1975 to quantify content validity at the Bowling Green University conference [81] and has continued to gain popularity ever since. CVR is calculated as depicted in Equation (8), while N denotes the total number of experts, and n_e is the number of experts indicating the questionnaire as a proper tool for the aims.

$$CVR = \frac{n_e - ({}^{N}/_{2})}{({}^{N}/_{2})} \tag{8}$$

In order to validate the survey questionnaire, ten experts were asked to rate the questionnaire content with regards to the relevance of the questionnaire to the sustainability factors on a 3-point Likert scale. The experts were asked if they judge that the main structural systems can affect the sustainability criteria in green buildings. The three choices were “not essential”, “beneficial but not essential”, and “essential.”

The CVR for individual items then becomes the ratio of experts that rated the item as relevant (in this case, rating 3 on the Likert scale) to the number of content experts. Table 2 provides the minimum acceptable values for CVR of different sample sizes (i.e., number of respondents). For this questionnaire, a CVR of 0.8 was obtained (with $N = 10\ and\ n_e = 9$), which is greater than 0.62, the minimum number for a sample size of ten respondents. Hence the questionnaire was regarded as “appropriate” for this study.

Table 2: The minimum values for CVR [81]

No. of Respondents	5	6	7	8	9	10	15	20	30	40
Minimum Value of CVR	0.99	0.99	0.99	0.75	0.78	0.62	0.49	0.42	0.33	0.29

2.3 Numerical simulations

In order to adequately quantify the environmental impacts of the two dominant types of structural frames (RC and SS frames) in Iran, the DesignBuilder and EnergyPlus software packages were used to model and simulate different building construction scenarios. It assists with the building energy and carbon performance assessment. The selection of these software packages [82] was based on the recognized accuracy of simulated results [83] and justified by their increasing influence on research related to the investigation of building thermal comfort [84], indoor environmental quality, carbon emissions [85], and shading performance of buildings [86]. The software helps architects and construction engineers design, analyze, and quantify the performance of buildings in a fast and accurate way [58]. Having an easy-to-use interface and fast calculations have led the designers to increasingly use this software package compared to other simulation tools.

3. Results

3.1 Identification of sustainability criteria in buildings

The first stage of the research is identifying sustainability criteria in buildings. A comprehensive review of the existing body of knowledge (journal articles, conference articles, book chapters, and standards) was used to gather secondary information about the main building sustainability criteria. It was necessary to rationalize the criteria to retain only the most important ones. This was achieved by conducting interviews with experts to assess the criticality of all the parameters identified from existing literature. As a result, the ten criteria shown in Table 3 were adjudged the most relevant and, in turn, formed the basis for subsequent analysis.

Table 3: The main sustainability criteria in buildings

No.	Name
C01	Internal air quality management
C02	Energy management
C03	Transportation management
C04	Water management
C05	Material management
C06	Site management
C07	GHG management

C08	Innovation and engineering management
C09	Waste management
C10	Labor management

The collected and collated raw sets of experts' opinions were qualitative; deducing quantifiable measures to enhance conceptualization would entail converting data to special quantitative formats. The subsequent stage of criteria identification is the validation by using the Fuzzy-Delphi Method (FDM) to guarantee all criteria' appropriateness. Responses were converted to 7-scale Fuzzy numbers, which was achieved based on a triangular scale method, as shown in Table 4.

Table 4: the fuzzy nomination of the answers

No.	Answers	Fuzzy Nomination
1	Not important	(0, 0, 0.1)
2	Very low importance	(0, 0.1, 0.3)
3	Low importance	(0.1, 0.3, 0.5)
4	Neutral	(0.3, 0.5, 0.75)
5	Important	(0.5, 0.75, 0.9)
6	Very important	(0.75, 0.9, 1)
7	Completely important	(0.9, 1, 1)

Equation (9) illustrates the mathematical description of the fuzzy arithmetic mean method, used to estimate the fuzzy number, where F, m, l and u respectively denote the triangular fuzzy number, arithmetic mean, minimum fuzzy number and maximum of the fuzzy number.

$$F = (\left\{\frac{\sum l}{n}\right\}, \left\{\frac{\sum m}{n}\right\}, \left\{\frac{\sum u}{n}\right\}) \qquad (9)$$

The raw outputs of FDM are an aggregated fuzzy set that must be defuzzified to obtain the best value from the set. Hence, Equation (10) was used to calculate the integrated fuzzy number for each criterion.

$$IF = \frac{l + m + u}{3} \tag{10}$$

The integrated fuzzy numbers generated per criterion based on Equation (10) are shown in Table 5. The minimum limit of IF for each criterion was 0.7. Criteria C09 and C10 can be observed to exhibit IF numbers that are less than 0.7. Hence C09 and C10 were rejected and omitted from the next stage.

Table 5: The integrated fuzzy numbers of criteria for two rounds

No.	Name	Integrated Fuzzy Number			Status
		1st round	2nd round	Margin	
C01	Internal air quality management	0.74	0.71	0.03	Accepted
C02	Energy management	0.80	0.82	0.02	Accepted
C03	Transportation management	0.75	0.72	0.03	Accepted
C04	Water management	0.82	0.75	0.07	Accepted
C05	Material management	0.79	0.76	0.03	Accepted
C06	Site management	0.71	0.73	0.02	Accepted
C07	GHG management	0.81	0.81	0	Accepted
C08	Innovation and engineering management	0.72	0.74	0.02	Accepted
C09	Waste management	0.66	0.65	0.01	Rejected
C10	Labor management	0.58	0.59	0.01	Rejected

Since after two rounds of the Delphi method were conducted, it is calculated that the differences between fuzzy numbers are less than 0.2, which is a minor margin. Finally, just two criteria (C09 and C10) were rejected, and the other eight criteria proceeded to the next stage.

3.2 Prioritization of sustainability criteria in buildings

Although the eight relevant criteria (C01-C08) were determined by FDM, their orders of importance are not equal. Therefore, it is imperative to understand each criterion's relative rank to support the cost-effective allocation of already scarce resources. The prioritization was implemented by asking the experts to assign relative importance weights to eight accepted criteria, after which the variables were ranked with the SWARA method. The outcomes of the process are given in Table 6.

Table 6: Ranking of the accepted sustainability criteria in buildings

Rank	Name	Sign	S_j	$K_j = s_j + 1$	q_j	w_j
1	Energy management	C02	---	1	1	0.160
2	GHG management	C07	0.021	1.021	0.979	0.156
3	Material management	C05	0.232	1.232	0.795	0.127
4	Water management	C04	0.006	1.006	0.790	0.126
5	Innovation and engineering management	C08	0.115	1.115	0.709	0.113
6	Site management	C06	0.025	1.025	0.692	0.110
7	Transportation management	C03	0.060	1.060	0.652	0.104
8	Internal air quality management	C01	0.039	1.039	0.628	0.100

It can be seen from Table 6, Energy management (C02) and GHG management (C07) were ranked significantly higher, with a disparity of approximately 18% between C07 and the Material management (C05) that was ranked third.

3.3 Calculating the impact of structural frames on the most important sustainability criteria

The effects of structural frames on the identified sustainability criteria were calculated using a 5-story building comprised of parking spaces at the basement and four residential floors. The 833-square meter building was modeled using DesignBuilder software under both SS and RC frames scenarios. The rebar ratio for

RC was 2.5%, and 20cm clay bricks made non-loaded walls. All four residential floors consisted of one unit, as depicted in the plan shown in Figure 4. The internal space was ventilated to 22°C, and 25°C setpoints for heating and cooling, respectively. All windows were double glazed, with a U value of 1.95 W/m^2.

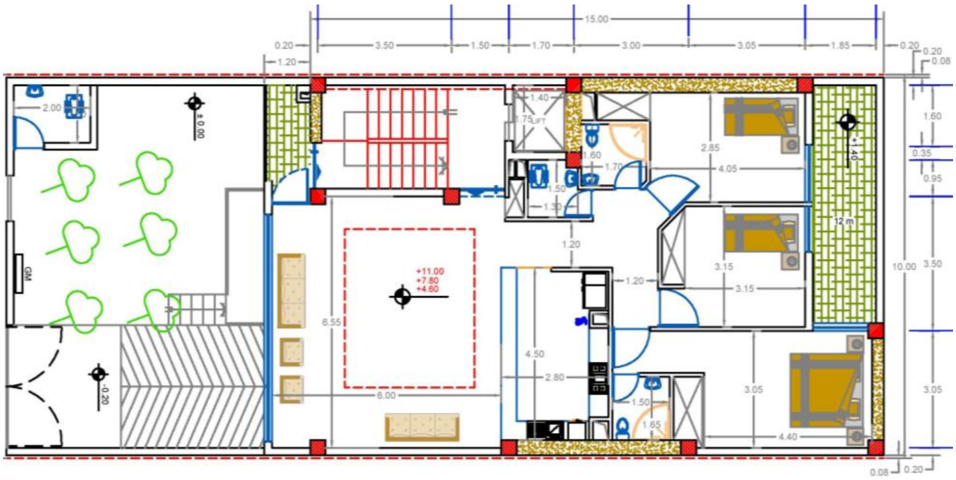

Figure 4: Typical plan of the building stories

In the model, electricity was used for lighting, cooling, and ventilation, while natural gas provided the energy needed for heating water and internal spaces. Figure 5 shows the operational energy consumption for the entire building.

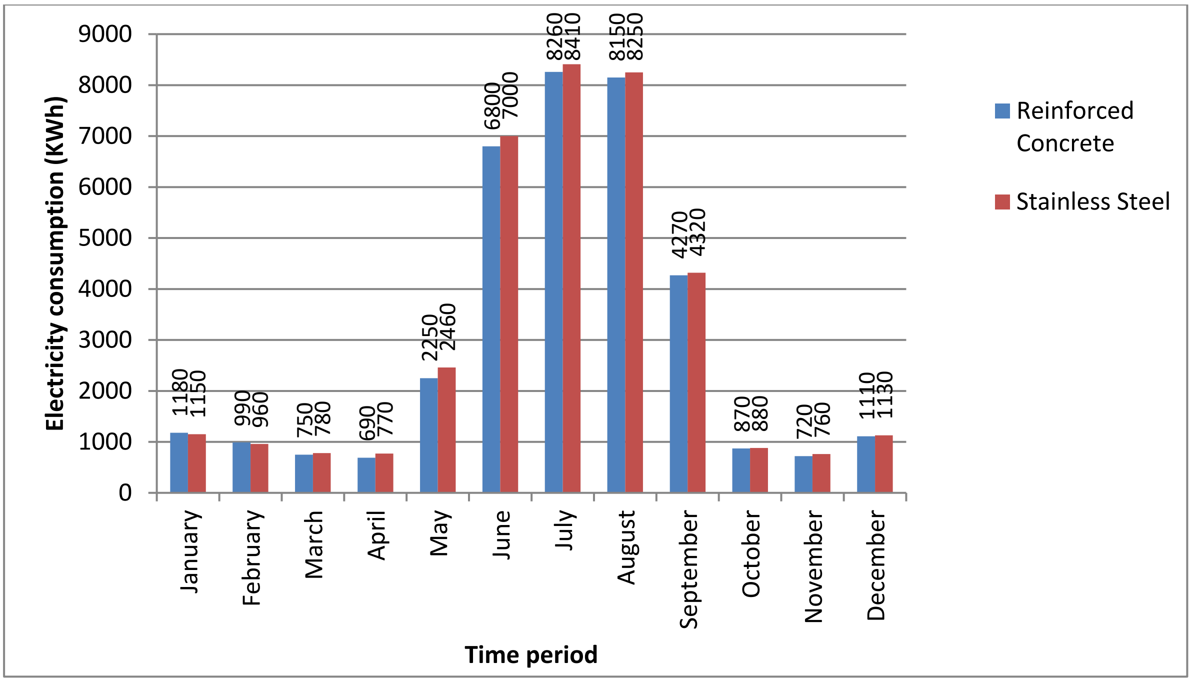

Figure 5: Monthly electricity consumption of RC- and SS-framed buildings

According to Figure 5, the annual electricity consumption for RC-framed buildings was 36,040 KWh, while that of SS-framed buildings was 36,870 KWh. These energy values indicate that the SS-framed building consumes approximately 2.3% more equivalent energy than the RC-framed building annually.

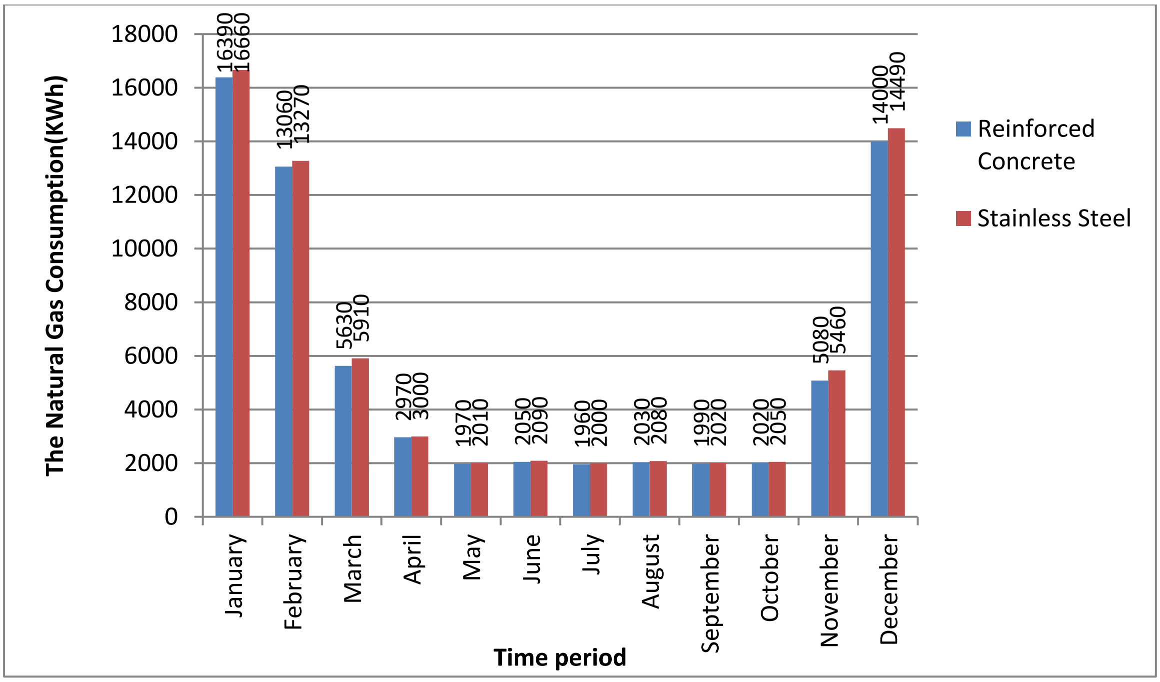

Figure 6: Monthly natural gas consumption of RC- and SS-framed buildings

Similarly, according to Figure 6, the annual natural gas consumption for RC and SS-framed buildings is 69150 KWh and, which implies that there could be up to a 2.7% reduction in energy consumption if an RC-framed structure shapes the building. It is important to note that the operational energy consumption varies by the temperature difference inside and outside the building. Table 7 provides the mean temperatures of the columns for all the months in a year. The internal air shows the mean temperature inside the rooms, living room, bathrooms, and the kitchen. The balcony and patio are not considered as internal spaces.

Table 7: Mean temperature of RC- and SS-framed structures

Month	RC			SS		
	Inside of columns	Outside of columns	Internal Air	Inside of columns	Outside of columns	Internal Air
January	12.8	11	16.3	11.7	11.7	16.3
February	13.5	12.1	16.5	12.6	12.6	16.5
March	17.2	16.7	17.7	16.6	16.6	17.7
April	21.4	21.7	20.5	21.5	21.5	20.7
May	27	27.5	24.9	27.1	27.1	25
June	30.5	32.1	26.3	31.2	31.2	26.4
July	31.3	33.3	26.7	32.3	32.3	26.8
August	31.3	33.1	26.7	32.1	32.1	26.7
September	28.9	29.8	25.7	29.3	29.1	25.7
October	24.2	23.7	23	23.4	23.4	22.8
November	18	17.2	18.6	17.2	17.2	18.5
December	12.4	12.4	16.7	11.8	13.6	16.6

The following important criterion considered was “GHG management,” Considering that CO_2 is the most impactful GHG to the building construction and operation, any intended optimization approach needs to commence with adequate knowledge of the amount of CO_2 emission. Figure 7 shows the monthly operational CO_2 emission.

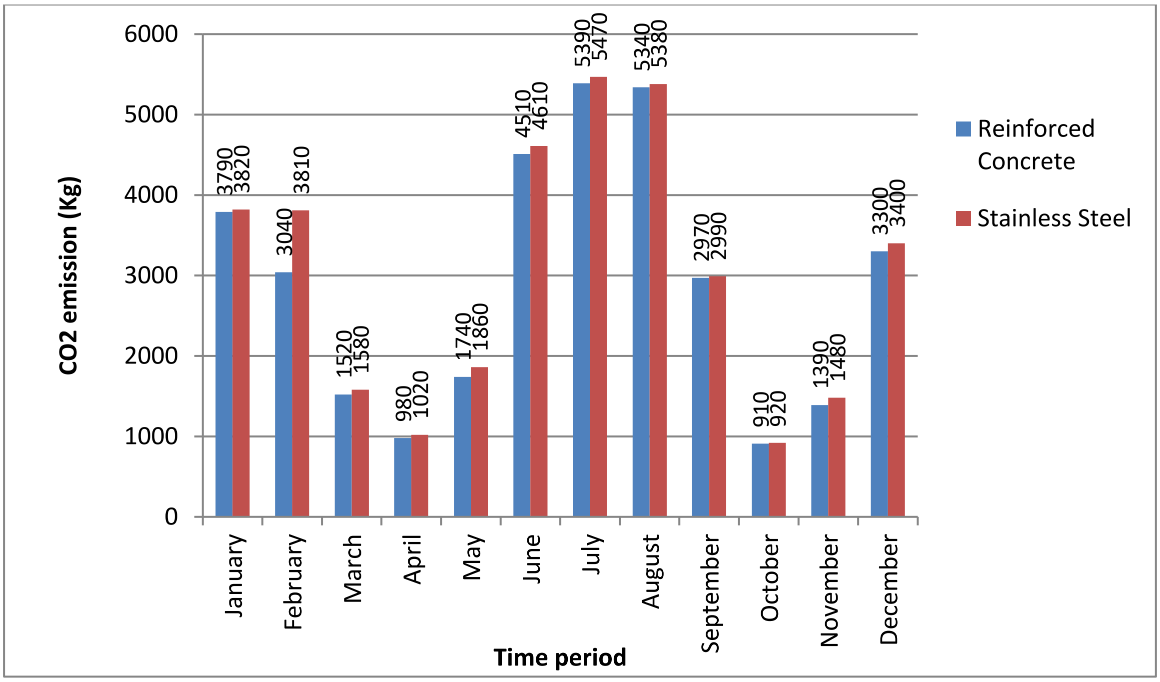

Figure 7: Monthly operational CO_2 emission for RC- and SS-framed structures

As can be seen from the results, RC-framed buildings have fewer carbon impacts. On the other hand, it is worth mentioning that recycling SS-frames in the buildings is highly beneficial to satisfy both environmental and economic aspects of sustainability. In order to adequately place the potential amount of CO_2 that a building emits throughout its lifecycle (50 years in this case) into perspective, Table 8 provides a comparative analysis of the CO_2 emitted by the different frames considered here at different lifecycle stages.

Table 8: Total CO_2 emission of RC and SS-framed buildings

Structural System	Annual CO_2 (Kg)	30-Year CO_2 (tonnes)	50-year CO_2 (tonnes)	Embodied CO_2 (tonnes)
RC-framed	34880	1046.4	1744	304
SS-framed	36340	1090.2	1817	321
Margin	1460	43.8	73	15

It is evident from Table 8 that RC-framed structures can offer a reduction of up to 88 tonnes of CO_2 emissions over 50 years (73 tonnes plus 15 tonnes of embodied

CO_2), which is more than 5% of the total emission attributable to a typical building throughout its lifecycle.

5. Discussion

The results show that main structural frames have a fundamental impact on the environmental sustainability of green buildings. From the literature review, it was observed that CO_2 is the most problematic GHG in the building industry. From the experts' opinions, it was conducted that labor management (C10) does not have a direct influence on environmental sustainability and was rejected by the Delphi approach. Another rejected item was waste management (C9) that according to [87], is formed from wastewater, construction waste, and demolition waste. Construction and demolition waste (CDW) can be investigated under material management (C5) and wastewater under water management (C4). Therefore, the experts did not accept this criterion as an independent criterion to scrutinize through the research.

After prioritizing the criteria, it was conducted that Energy and GHG management (C2 and C7) were the most important items by the weights of 0.160 and 0.156, respectively. It shows the significance of global warming and the detrimental effects on our lives from the experts' perspective.

The third rank was held by material management (C5) with a relative weight of 0.127. Since the materials coming from nature are not infinite, to have an environmentally sustainable construction, they should be administered. According to previous studies, it is highly accepted that the most beneficial stage to act in is the design stage. In the current research, structural frames, as one of the most crucial parts of the buildings, are modeled and analyzed. Since most structural systems in

Iran are out of RC or SS, the modeling process was shaped based on these two types of frames. Furthermore, high-rise buildings worldwide are mainly designed and built by RC and SS structural systems.

Water management (C4), in line with the research by [27], is a prominent environmental issue in green buildings with a relative weight of 0.126. Clean water access and water reuse are the most crucial factors in the water management (C4) criteria.

Innovation and engineering management (C8) with the relative weight of 0.113 is the following criterion contributing the engineering-related stages in the project and using innovative approaches for the modeling and designing green buildings.

The other criteria are site management (C6) with the relative weight of 0.110, Transportation management (C3) with 0.104, and Internal air quality management (C1) with the weight of 0.100 in the environmental sustainability criteria.

In the end, the effects of changing the main structural frames on green buildings were calculated by modeling a case study. The results show that SS-framed buildings have a more detrimental impact on the environment, owing to more energy consumption for the production process, more energy waste during the operational period, and more GHG production for manufacturing the materials.

It was observed that RC-frames were 2.3% more efficient than SS-frames regarding operational electricity consumption and 2.7% natural gas consumption. Furthermore, in a 50-year span, RC frames can reduce operational CO2 emissions by up to 73 tons, plus additional 15 tonnes of embodied CO_2.

The results align with previous studies showing that RC buildings are more environmentally friendly than their SS counterparts. Peyroteo et al. mention that RC-framed buildings use 80% less energy and more than 80% less CO_2 for production [49]. However, the current study results show much less margin (5%) between the two systems.

Since there are varieties between the weather conditions in various places, the results would differ in different countries and even cities. Moreover, the embodied energy for each material is based on transportation needs, manufacturing technology, and production process. Thus, different results in different studies can be approved.

However, Xing et al. calculates the Energy consumption of a building and declares that steel construction consumes less energy and produces less CO_2 than concrete construction. They calculate the CO_2 emission of RC twice as the SS buildings and 33% more energy consumption in RC compared to SS buildings [88].

6. Conclusion

The detrimental impact of the construction industry on the environment is vastly discussed in previous studies. To reduce the harm of buildings to our environment, the sustainability criteria must be identified, and various effects of the main building members should also be considered. In this research, since one of the crucial parts of buildings is the main structural frame, the sustainability criteria were initially identified and then prioritized according to experts from the building construction field in Shiraz, Iran. The mentioned criteria were initially gathered from secondary sources through a comprehensive review of the existing body of knowledge (including journal articles, conference articles, book chapters, and standards) and then narrowed by the interview with experts and reduced to ten. A fuzzy-Delphi method (FDM) was then used in two rounds to further rationalizing the ten criteria initially generated from experts' opinions to a final eight criteria. In order to establish the relative order of importance of the criteria, the SWARA method was employed, which indicated that "Energy management" and "GHG management" were the most important items. Lastly, to quantify the influences of structural frames on eight sustainability criteria, a building was simulated for two different scenarios (SS and RC structural frames) using the DesignBuilder software.

The approach described in this study is simple, quick, but most importantly applicable to any region of the world, where the needed data related to total sunshine hours, humidity, building layout, and dry bulb temperature is available. The provided simulation process is dynamic in terms of calculation and is fully responsive to the variables such as materials and weather conditions.

However, considering that external temperature plays a fundamental role in heat transfer, air conditioning, and ventilation demand, one perceived limitation of this study would be the regional concerns and the potential impacts on the repeatability of the outcomes reported here. Therefore, future research activities can be planned to apply the same concepts described here to several case studies from regions with significantly diverse climate patterns. In addition, future climate patterns are able to affect the results and must be observed.

Further investigations may use the methodology and the results to calculate the effects of main structural frames on six other mentioned criteria. Other criteria or the approach classification can lead to a different comprehensive set of criteria that should be noticed in future research.

The construction industry stakeholders (clients, project sponsors, project and construction managers, building engineers) could employ the results for selecting the main structural frames of buildings regarding sustainability matters in green buildings. Not only the environmental impacts of main structural frames can be seen in designs, but also the cost of the energy reduction (or increase) can be analyzed with the results of the current study.

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