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A Novel Building Information Modeling-based Method for Improving Cost and Energy Performance of the Building Envelope

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P A P E R I N F O	*A B S T R A C T*
Paper history: Received 24 May 2020 Received in revised form 30 August 2020 Accepted 02 September 2020 *Keywords*: *Building Information Modeling* *Building Envelope Materials* *Energy Consumption* *Life Cycle Cost*	Building envelopes and regional conditions can significantly contribute to the cost and energy performance of the buildings. Structured methods that take into account the impacts of both the envelope materials and the regional conditions to find the most feasible envelope materials within a region, however, are still missing. This study responds to this need by proposing a novel method using the capabilities of Building Information Modeling (BIM). The proposed method is used for identifying cost- and energy-efficient building envelope materials within a region over the life cycle. First, commonly used envelope materials in a region are identified. Then, BIM is employed for simulating the energy performance and evaluating the life cycle cost of the materials. The method was implemented in Tehran, Iran. It was successfully utilized for improving the cost and energy performance of a nine-story residential building case. The achieved results indicated a potential energy performance enhancement of 31%, and the life cycle cost improvement of 28% by replacing conventionally used envelope materials with the available high-performance building materials. The proposed method can benefit various stakeholders in the building construction industry, including municipalities, owners, contractors, and consumers, by enhancing the cost and energy performance of the buildings.

1. INTRODUCTION

Selecting an appropriate type of building envelope can have a considerable impact on the cost and energy performance of buildings. It is estimated that more than 20% of a building's construction cost is spent on the building envelope [1, 2]. The building envelope forms the border between the interior and exterior of the building. Therefore, a majority of the building's heat exchange during the operation period occurs via the envelope. The high impact of the building envelope on the life cycle cost and energy performance of the buildings has inspired many researchers around the globe. Researchers have examined the impacts of different building envelope materials and insulators on the cost and energy performance of the buildings. Sawhney et al. [3] compared the cost efficiency of very energy-efficient (or Five Star) and super energy efficient (or Five Star Plus) materials. They found a shorter payback period for Five

Star materials in Michigan, USA. Cheung et al. [4] found a potential average energy consumption savings of 31% for high-rise apartments in the hot and humid climate of Hong Kong using extruded polystyrene (XPS) insulation layers. Hoseini et al. [5] found the use of fiberglass insulation in the brick walls and ceilings with the double-glazed windows results in a 49% reduction in the energy-saving in Tehran, Iran. Domínguez et al. [6] identified a potential energy saving of up to 27% with a proper selection of insulation materials in Seville, Spain. Sim and Sim [7] found energy performance deviations for different types of wall materials, including mud brick, cement brick, autoclaved light-weight concrete block, cellulose fiber reinforced cement board, and chaff charcoal, in traditional Korean buildings. Braulio-Gonzalo and Bovea [8] found the use of mineral and glass wool insulations highly effective in saving energy in the buildings in Spain. Echarri [9] reduced the annual energy consumption of a detached residential building in Spain

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by 10% using thermal ceramic panel walls. Pakand and Toufigh [10] found the energy efficiency of low-cost rammed earth wall materials comparable to the high-cost Expanded polystyrene insulation (EPS) and phase change materials. Rahbar and Saadati [11] showed the use of polystyrene insulation layers could improve the energy performance of the buildings by up to 6.5% in the hot and dry climate of Semnan, Iran. Song et al. [12] analyzed the impacts of EPS insulation materials on the energy consumption of an office building in Southern China. Hasan et al. [13] found phase change envelope materials can reduce the energy consumption of buildings.

Impacts of regional conditions on the cost and energy performance of the building envelope have also been investigated in past research. Masoso and Grobler [14] identified the use of 80 mm XPS insulation in buildings results in the energy-saving up to 26 degrees Celsius and the waste of energy beyond this temperature in a hot and dry climate. Pulselli et al. [15] examined the energy performance of three different types of building envelope materials in three regions in Europe. The study found the regional climate condition as the main factor affecting the performance of different building envelope materials. Additional building insulation resulted in different life cycle cost savings in four cities in Turkey [16]. Ramesh et al. [17] found that the use of insulation materials could result in a range of 10% to 30% energy savings in five different climate zones in India, depending on the climate conditions. Friess et al. [18] identified different impacts for insulation materials in typical office buildings across Malaga (Spain), Dubai (UAE), and El Dorado (USA). Climate condition was also identified as the main contributing factor to the energy performance of the buildings' envelope insulation materials in Greece by Charisi [19].

Since the emergence of Building Information Modeling (BIM), the employment of BIM for Building Energy Modeling (BEM) has become quite popular [20, 21]. BIM encompasses a detailed integrated multi-discipline design of the buildings to provide necessary input data for BEM in a cost and time-efficient manner [22–24]. BIM models can also provide foundations for capturing the regional and environmental impacts on the energy performance of the buildings [25]. Furthermore, material quantity takeoff and cost estimation is a frequently used application of BIM models in the building construction projects [26]. In the past, the low accuracy level of the building's cost estimation [27] and energy performance analysis [3] performed with traditional methods was a significant issue. BIM could considerably enhance the accuracy level of cost estimation [27] and life cycle energy performance analysis [25] and address this concern of the traditional methods.

The capabilities of BIM to facilitate and improve BEM development have encouraged many researchers to apply BIM in their building performance improvement efforts. Niu et al. [28] developed a BIM-GIS (geographical information system) integrated web-based database of regional energy-efficient building design for urban development. More specifically, some researchers have utilized BIM for optimizing building design options. Jalaei and Jrade [29] proposed a BIM-based integrated life cycle assessment platform for analyzing the environment cost of buildings with different sustainable-certified building components. Oduyemi and Okoroh [30] employed BIM as a useful information-based tool for analyzing the effect of increasing insulation to roof and windows and occupancy level on the indoor environmental quality. Ahsan et al. [31] used BIM for the selection of most efficient insulation materials and their optimum thickness to improve the cost and energy performance of existing buildings in Pakistan. Lim et al. [32] developed a BIM-based method for automatically calculating the thermal values and construction costs of available building envelope choices. Shalabi and Turkan [33] developed a BIM-energy simulation method to identify building spaces with abnormal energy consumption behavior.

Past research identifies BIM as a powerful tool for comparing different aspects of the available building envelope materials. Nevertheless, the past research lacks a structured method that guides practitioners for identifying cost- and energy-efficient building envelope materials within a region over the life cycle. This research fills this gap by proposing a novel BIM-based method to assist building practitioners. The proposed method considers regional conditions affecting the performance of buildings, including weather conditions, availability of the energy carriers and construction materials in the region, energy carriers' costs, and construction materials' costs. First, different parts of the proposed method are outlined. Then, the capability of the proposed method is verified during its implementation for the buildings in Tehran, Iran. Finally, the results achieved in the research are discussed and concluded.

2. PROPOSED METHOD

Various regional conditions, including climate conditions, energy and material availability, cost, and construction method, contribute to the final cost and energy performance of the building envelope materials over the life cycle. Identified cost- or energy-efficient materials within a region are not necessarily efficient in another region. Therefore, in addition to the material properties, the proposed method needs to capture the regional conditions to accurately identify cost- and energy-efficient building envelope materials within a region. The use of efficient envelope materials that are not accessible in a region is not feasible. The proposed

method does not consider the creation of supply chains for the materials and new investments in capacity development for producing unavailable or new materials within the region. Therefore, in the first part of the proposed method, the commonly used and accessible building envelope materials and the alternative building envelope scenarios in the region are identified. In the next part, the BIM models of a sample building are developed for the rival envelope scenarios. The BIM models encompass detailed specifications of each scenario, including geometrical information of the building, type of materials, material density, and thermal conductivity of the material. This information can facilitate the life cycle cost estimation of the building's envelope in the next part of the proposed method.

In the third part of the proposed method, the BIM models are hired for extracting the material quantities and simulating the annual energy consumption of the building. Estimated material quantities are used for the cost estimation of the building envelope construction and maintenance using locally collected cost rates. Locally regulated cost of energy carriers, e.g., natural gas and electricity, are used for the estimation of the energy cost of the building over the operation years. In the last part of the proposed method, the life cycle cost of each scenario, considering the construction and maintenance cost of the building envelope, and the operational cost of the building is estimated. Here, the construction cost includes the building's envelope material cost, installation cost, and transportation cost, which occur during the construction period. The maintenance cost consists of the annual cost spent on preventive and corrective maintenance activities to maintain the required level of service during the operation period. The operational cost includes the overall building's energy consumption cost during the operation period. The accounted costs of each scenario occur during different periods of the building's life cycle. However, to compare the performance of different adopted scenarios, a single value representing each scenario is required. Net Present Value (NPV) represents the equivalent present value of a set of cash flows occurring in different periods. Here, the

calculated NPV of each scenario is proposed as the indicator of each scenario's performance. Figure 1 represents the resulting cash flow and the applicable calculation equation of each scenario's NPV. Figure 2 summarizes the different parts of the proposed method.

3. METHOD IMPLEMENTATION

Tehran is the capital and the most populated city in Iran. According to SCI [34], approximately one-fourth of new residential building areas within the country are built in Tehran. The significant impact of Tehran's residential building construction market in the country was the main contributing reason for selecting Tehran for the sample implementation of the proposed method. Approximately 95 percent of residential buildings in the city are multi-story buildings with five floors or more [34]. In multi-story buildings, the exterior walls have the highest thermal transfer surface area and consequently bear a significant share of the energy loss. As a result, the proposed method in this research was implemented for improving wall materials of multi-story buildings in Tehran. The proposed steps were followed to identify the most viable wall construction materials in the city. A more in-depth explanation of the various steps is provided in the remainder of the section.

3. 1. Identifying Prevalent Materials   The first step of implementing the proposed method for Tehran was to identify the frequency of various available materials in the region. At the time, no information was found regarding the frequency of different available building envelope materials in Tehran. Therefore, the research team directly performed a field survey on various building construction companies in Tehran for identifying common building envelope materials in the city. An inclusive list of materials used in three main components of the building envelope, including walls, façade, and windows, was created according to the reported articles from different sources [33–36]. According to Golabchi and Mazaherian [36], various
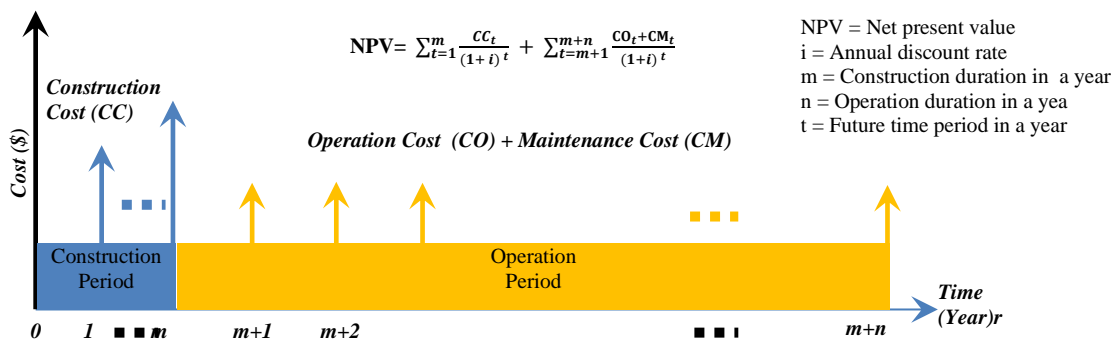
$$NPV= \sum_{t=1}^{m} \frac{CC_t}{(1+i)^t} + \sum_{t=m+1}^{m+n} \frac{CO_t+CM_t}{(1+i)^t}$$

NPV = Net present value
i = Annual discount rate
m = Construction duration in a year
n = Operation duration in a yea
t = Future time period in a year

Figure 1. Schematic view of the life cycle cash flow related to the building envelope
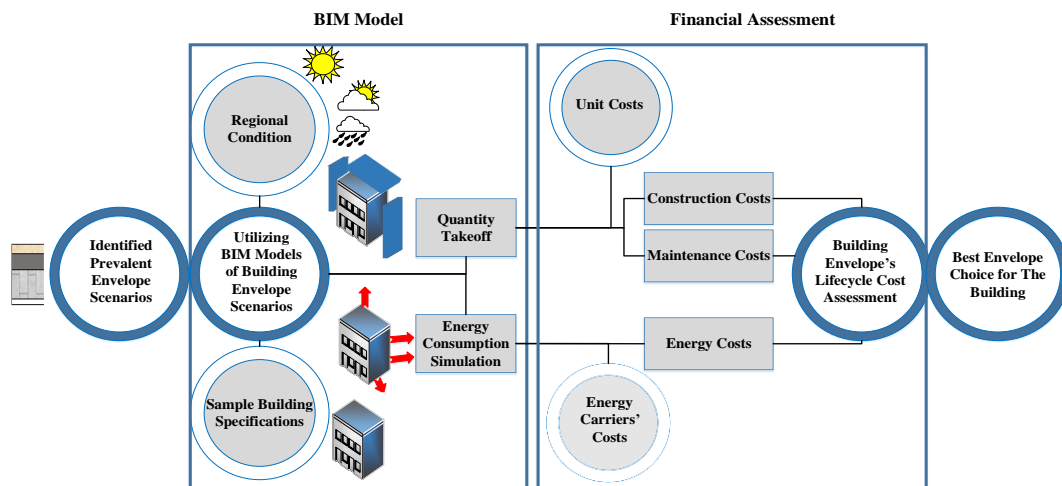
Figure 2. Different parts of the proposed method

exterior wall structures in the region could be divided into three main groups, including traditional, semi-industrial, and industrial. This approach could capture emerging building envelope materials. Table 1 presents the list of materials organized under the adopted categorization method. This material list was then utilized in the field survey to identify and rank the most common building envelope materials in Tehran.

3. 1. 1. Survey Design   Building construction companies in Tehran were the target group of the statistical survey. A data sampling method using a questionnaire survey was adopted for ranking the frequency of the identified building envelope materials. The frequency of various building envelope materials was questioned using five-level Likert scale questions ranging from 1 to 5.

3. 1. 2. Questionnaire Distribution   The 64 paper-form questionnaires were distributed and collected through an in-person questionnaire distribution method. IBM SPSS software was then employed to analyze the collected data. Cronbach's alpha value of 0.881 affirmed the reliability of the responses. The relational consumption frequency level of different materials was calculated as the average value of the responses received for each question. Table 1 presents the achieved average consumption frequency and the ranks of different identified envelope materials in the survey.

3. 1. 3. Survey Analysis   The achieved results for the wall materials represent higher consumption frequency levels for the most traditional materials than the emerging semi-industrial and industrial materials. Among various wall materials, two traditional materials of clay block and expanded clay concrete block received the highest rank with the respective values of 3.87 and

TABLE 1. List of available residential building envelope materials and their achieved consumption frequency in Tehran

Component	Production method	Material	Frequency value (out of 5)	Rank in group
Wall	Traditional	Brick	2.05	7
		Clay Block	**3.87**	**1**
		Expanded Clay Concrete Block	**3.47**	**2**
		Sandcrete block	2.85	3
		Perlite Concrete Block	2.10	6
	Semi-Industrial	Aerated Block	1.40	9
		Cement board	1.72	8
		EPS Concrete Block	**2.15**	**5**
		Light-weight Concrete Panel	**2.17**	**4**
	Industrial	**3D Panel**	**2.17**	**4**
		Precast Concrete Panel	**1.40**	**9**
Façade		Granite Stone	2.65	4
		Travertine Stone	**4.17**	**1**
		Sandstone	1.47	14
		Limestone	2.22	6
		Sedimentary Stone	1.97	8
		Other Stones	0.22	16
		Brick	3.07	3
		Cement	3.37	2
		Aluminum Composite Panel	1.95	9
		Glass	2.50	5
		Low-E Glazed	1.82	10
		Ceramics	2.00	7

Concrete Panel	1.60	12
Stretch Metal	1.22	15
HPL	1.57	13
Fibre Cement Board	1.67	11
Iron-Single Glazed	1.68	9
Iron-Double Glazed	1.53	11
Iron-Triple Glazed	1.15	14
Iron-Low-E	1.09	15
Iron-Reflex	1.56	10
Aluminum-Single Glazed	1.78	7
Aluminum-Double Glazed	2.84	2
Aluminum-Triple Glazed	1.78	7
Aluminum-Low-E	1.46	12
Aluminum-Reflex	2.37	4
UPVC-Single Glazed	2.09	5
UPVC-Double Glazed	**4.15**	**1**
UPVC-Triple Glazed	1.93	6
UPVC-Low-E	1.28	13
UPVC-Reflex	2.59	3

(The "Window" label spans the rows from Iron-Single Glazed to UPVC-Reflex.)

3.47. Light-weight concrete panels and EPS concrete blocks scored the best ranks among the semi-industrial materials with the respective values of 2.17 and 2.15. The

values for the two industrial wall materials of 3D panels and precast concrete panels were 2.17 and 1.40, respectively. Among different façade materials, travertine stone tiles were by far the most commonly used material with the consumption frequency value of 4.17. In the window systems, UPVC-double glazed was the dominant system with the consumption frequency level of 4.15. Subsequently, six different building envelope material scenarios were formed by choosing the two most common wall materials from the three production methods. Figure 3 presents the considered specifications in different scenarios. In all six scenarios, the UPVC-double glazed window was used since it was the most dominantly used window system. Travertine stone façade attached to the wall by cement mortar for the visible sides or the street-facing sides of the buildings was used in all scenarios. However, the concealed exterior sides of the building were only covered by cement mortar. Plaster and earth plaster (if required) were considered for leveling the interior side of the walls as a commonly used method. The performance of these six scenarios was analyzed and compared in the case of Tehran following the proposed method.

3. 2. Building Case Specification   An under-construction, nine-story residential building with a reinforced concrete structural system in Tehran was used for the case study. The area of each floor was 716 square meters. The cost estimation performed by the construction team indicated the share of the entire envelope construction cost exceeds 22% of the building construction cost. The air conditioning system was a two-pipe fan coil system using a central chiller with a 5.96 coefficient of performance for the cooling and a central boiler with an 84.5% efficiency rating for the heating.
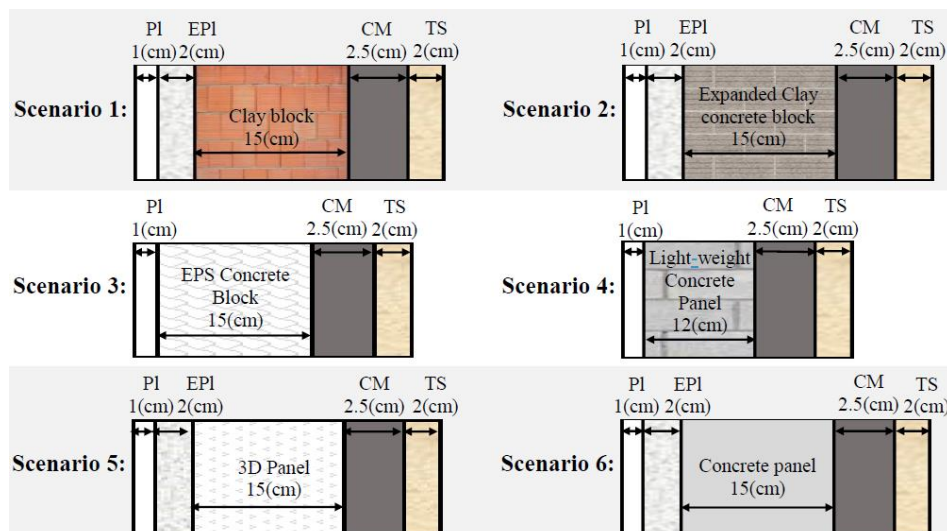
Figure 3. Specifications of different adopted building envelope scenarios, Pl: Plaster; EPl: Earth Plaster; CM: Cement Mortar; TS: Travertine Stone; Sh: Shotcrete; EP: Expanded Polystyrene

3. 3. Wall Construction Cost   BIM-based 3D models of different building scenarios were developed by the collaborating construction company using Autodesk Revit software. The developed models had a level of detail of 300 to encompass the material specification and air conditioning system of the building [37]. Figure 4 illustrates the floor plan and 3D view of the developed BIM model of the building. The BIM technology for the material quantity takeoff was used for extracting the volume of different envelope materials. Construction methods of three to four different past building projects were assessed for estimating the resource required and cost spent in each building envelope scenario. Unit prices of the transportation and construction costs of different parts of the building's envelope were collected from the corresponding subcontractors in the market. Overall, the construction costs of different adopted scenarios were estimated based on the extracted quantities and prices for different scenarios. Table 2 presents the estimated construction cost of the walls in different scenarios. Among different scenarios, Scenario 1 or the base scenario, which uses the clay block materials, is the most frequently consumed in Tehran, represents the lowest overall construction cost. Scenario 3 with EPS concrete blocks scored the highest construction cost, among other envelope materials.

3. 4. Energy Consumption Simulation   Thermal specifications of the adopted construction materials were collected from the corresponding references and were
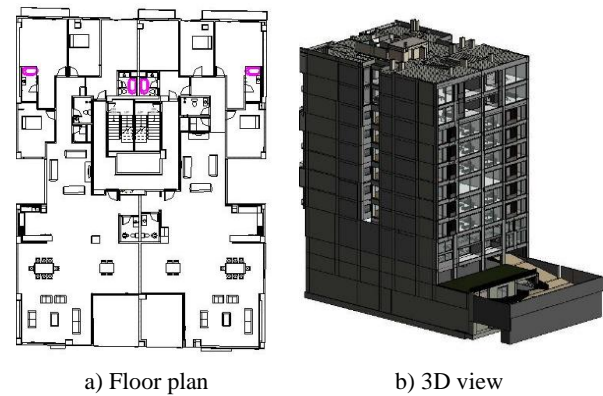
a) Floor plan   b) 3D view
Figure 4. Floor plan and 3D view of the building

added to the BIM models. Autodesk® Green Building Studio software, which effectively works with BIM models to simulation the energy performance of the buildings, was selected in the research. The simulation software imported the thermal specification of the materials and the spatial dimensions of the building from the BIM model. The regional climate condition received from Mehrabad international airport's weather station in Tehran and the comfort temperature of 25 degrees Celsius was also directly introduced to the simulation software. The BIM-based energy simulation software was then used for estimating the monthly energy consumption of each building scenario during the operation phase. Table 3 presents the extracted thermal

TABLE 2. The estimated construction cost of the envelope materials in different scenarios

Scenario	Material purchase cost ($)	Wall surface area (m²)	Wall installation unit cost ($/m²)	Total installation cost ($)	Transportation cost ($)	Overall construction cost ($)
1	54,514	2,862	1.67	4,770	1,726	**61,010**
2	64,736	2,862	1.67	4,770	1,908	**71,414**
3	106,984	2,862	1.19	3,407	3,082	**113,473**
4	57,921	2,862	11.90	3,4071	1,629	**93,622**
5	88,586	2,862	3.57	10,221	1,671	**100,478**
6	68,143	2,862	11.90	34,071	236	**102,450**

TABLE 3. Thermal properties of different scenarios introduced to the BIM model

Production Method	Scenario	Thickness (m)	Overall Thermal Resistance ($m^2 \cdot k/w$)*	Source
Traditional	1	0.22	0.25	BHRC [35]
	2	0.22	1.37	BHRC [35]; Leca [38]
Semi-Industrial	3	0.20	1.11	BHRC [35]; Khane Irani Group [39]
	4	0.17	0.90	BHRC [35]; Bastanpol [40]
Industrial	5	0.17	2.62	BHRC [35]; Mohammad Kari and Ahmadi [41]
	6	0.18	0.16	BHRC [35];
Window	All		0.32	

specifications of the adopted construction materials from the corresponding references. Figures 5 and 6 present monthly and annual electricity and natural gas consumption estimated for different scenarios.

Interestingly enough, Scenario 1 with the clay block materials, represented the highest overall energy consumption among all six scenarios. The scenario with the light-weight concrete panels presented the lowest total energy consumption. The standing of different scenarios in the separate electricity and natural gas consumption, however, follows a different trend. Scenario 2, with the expanded clay concrete block materials, presented the highest electricity consumption. Scenario 6, with the precast concrete panels, consumed the least annual electricity. In a changing mood, Scenario 6 represented the highest natural gas consumption,

among other scenarios. Scenario 4, with the light-weight concrete panels, presented the lowest natural gas consumption. In general, semi-industrial and industrial scenarios considerably showed less overall energy consumption compared to the traditional scenarios.

3. 5. Energy Consumption Cost   Iran's government regulates and controls the cost of electricity and natural gas in different parts of the country during different parts of the year. A portion of the energy price is subsidized, and incremental cost rates are applied when monthly electricity and natural gas consumption are increased [42]. Tables 4 and 5 present the incremental rates of electricity and natural gas costs set by the government in Tehran in 2018. Therefore, the estimated monthly energy consumption by BIM-based energy
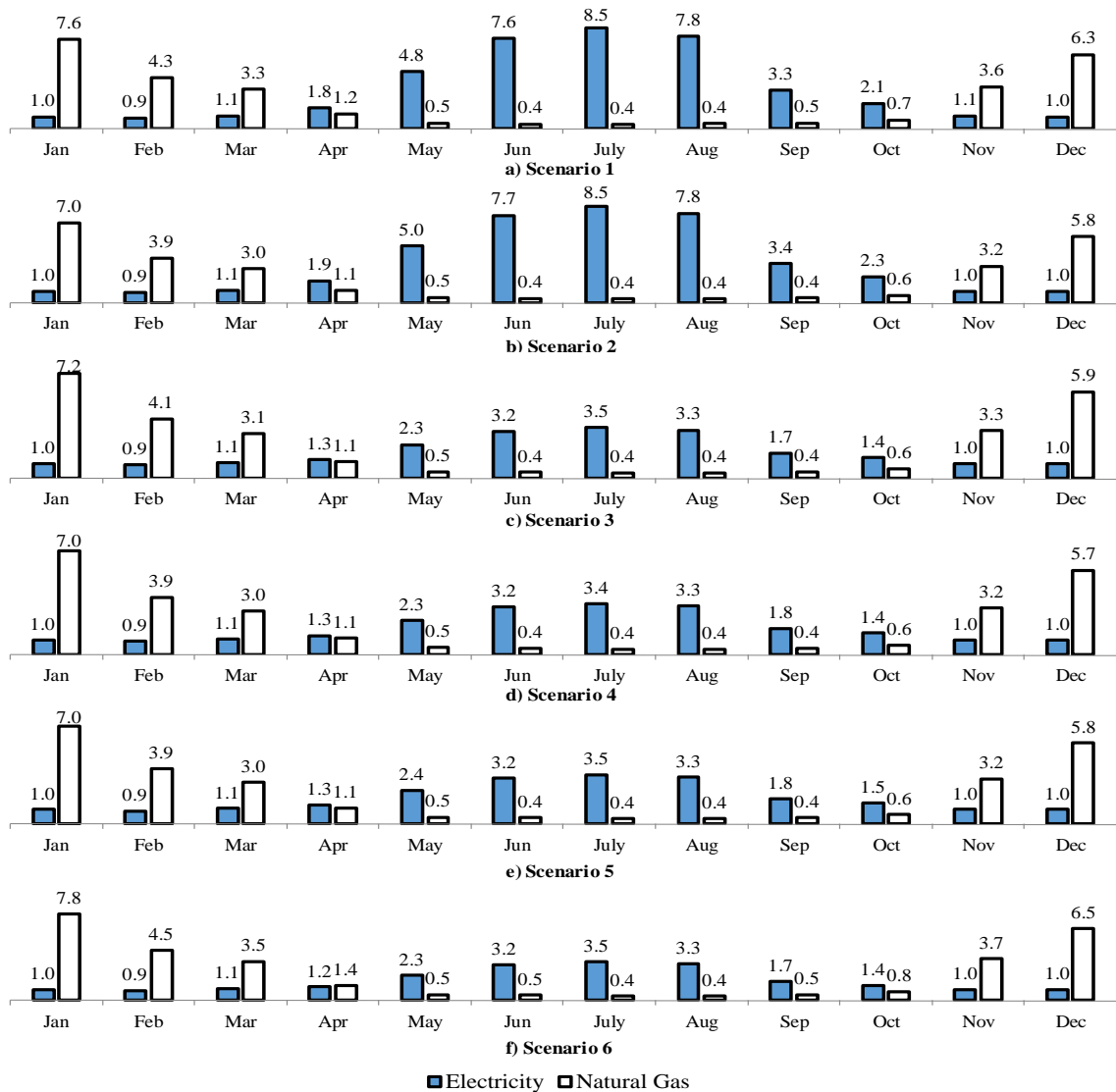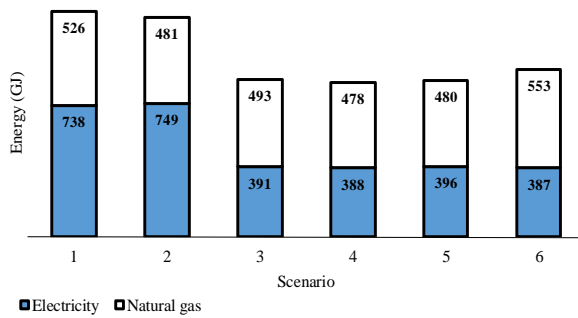

Figure 5. Monthly energy consumption distribution (GJ)

Figure 6. Estimated annual energy consumption by BIM-based energy simulation software in different scenarios

simulation software was used for estimating the building's energy consumption cost. Table 6 presents the summary result of the annual energy consumption costs of different scenarios. Also, annual energy consumption by BIM-based energy simulation software is illustrated in Figure 6.

3. 6. Financial Assessment   Despite the high energy consumption of the traditional wall scenarios, these scenarios were most frequently consumed in the construction market of Tehran due to their low construction costs. The low construction cost of materials, however, does not necessarily result in an overall low cost. The operation cost of the building during the operation period can play a detrimental role as well. The life cycle cost of six different envelope scenarios was estimated by concurrently capturing construction, maintenance, and operating costs. The cash

flow of each scenario was formed by accounting the construction cost of walls, and annual energy consumption cost of the building during the 30 years of the building's life cycle. According to the field study from different building construction and maintenance companies, the maintenance cost of the building envelope is trivial during the first ten years of the building construction. The main portion of the maintenance cost is spent on the building façade and the interior plaster. These two components of the envelope stay the same in all of the adopted envelope scenarios. Therefore, the maintenance cost in different scenarios was considered constant and was not added to the cash flow.

The net present value (NPV) was calculated with a discount rate of 15%, equal to the interest rate of a bank investment account [43], and the officially announced inflation rate of 9.5% [44]. Table 7 summarizes the financial calculation results in different scenarios. Figure 7 also presents the rank of different scenarios in various aspects. Among different scenarios, Scenario 4, with the light-weight concrete panels, resulted in the minimum life cycle cost. This scenario also represented the least energy consumption among all scenarios. It was ranked 3rd in the consumption frequency and the construction cost. Here, two traditional scenarios, the first and second, with the highest consumption frequency rates, showed the highest NPV of the building envelope's life cycle cost and the lowest energy performance. The achieved results represented a potential of a 31% reduction in energy consumption during the operation phase and a 28% reduction in the envelope life cycle cost of the building.

TABLE 4. Electricity price in Tehran in different consumption ranges

Step	1	2	3	4	5	6	7
Consumption Range (KWh)	0-100	101-200	201-300	301-400	401-500	501-600	Over 600
Cost* (US¢ / KWh)	1.07	1.25	2.68	4.82	5.54	6.97	7.68

* Exchange rate of 42500 Iranian Rial per US dollar was considered according to CBI [45]

TABLE 5. Natural gas price in Tehran in different consumption ranges and seasons

	Step	1	2	3	4	5	6	7	8	9	10	11	12
Apr. – Oct.	Consumption Range (m³)	0-45	46-95	96-145	146-195	196-245	246-295	296-345	346-395	396-445	446-495	496-545	Over 545
	Cost* (US¢ / m3)	2.57	3.12	3.94	5.04	6.13	6.68	7.50	8.32	8.87	9.42	9.97	10.24
Nov. –Mar.	Consumption Range (m³)	0-200	201-300	301-400	401-500	501-600	601-700	701-800	801-900	901-1000	1001-1100	1101-1200	Over 1200
	Cost* (US¢ / m3)	0.99	1.64	2.25	2.96	3.61	5.50	6.24	7.23	8.21	9.20	10.51	11.50

* Exchange rate of 42500 Iranian Rial per US dollar was considered according to CBI [45]

TABLE 6. Annual energy cost of different building envelope scenarios (USD)

Scenario	Electricity Cost	Natural Gas Cost	Total Energy Cost
1	$17,085	$2,598	$19,683
2	$18,136	$2,283	$20,420
3	$8,391	$2,371	$10,762
4	$8,350	$2,260	$10,611
5	$8,640	$2,275	$10,915
6	$8,334	$2,769	$11,104

TABLE 7. Cost and energy performance of scenarios over the building's life cycle (USD)

Scenario	Construction Cost	Annual Energy Cost	Life cycle NPV	Payback Period*
1	$61,010	$19,683	$292,713	-
2	$71,414	$20,420	$310,726	Never
3	$113,473	$10,762	$229,715	8 Years
4	$93,622	$10,611	$210,603	5 Years
5	$100,478	$10,915	$220,277	6 Years
6	$102,450	$11,104	$224,283	7 Years

* Payback period is calculated in comparison to Scenario 1 or the base scenario.
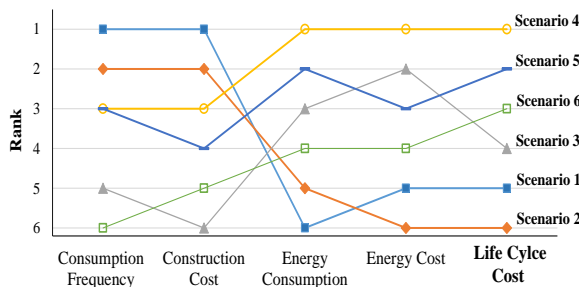
Figure 7. The rank of different scenarios in various aspects

The payback period of different scenarios in comparison to Scenario 1 (i.e., the base scenario) is presented in the last column of Table 7. Scenario 1 provides the lowest construction cost among the others. Therefore, project owners pay high construction costs when they opt for other wall construction scenario than the base scenario. In scenarios with lower operating costs than the base scenario, the additional construction cost is gradually paid off. Except Scenario 2, which provides both higher construction and operation costs than Scenario 1, additional construction costs are returned for the other four scenarios after a while. Expectedly, Scenario 4 represents the shortest payback period of 5 years among different scenarios.

4. RESULTS AND DISCUSSION

The survey results identified low-price and traditionally produced wall materials as the most commonly used materials in the residential building construction in Tehran, Iran. The achieved results show that building developers are more concerned about the initial construction costs than the energy consumption and the operating costs of buildings. Currently, many investors who are not the end-users of buildings invest their money in building construction projects. These investors, who make up the first group of builders, are not the ultimate consumers of the buildings and are not concerned by the high energy consumption nor the high operation cost.

On the other hand, residential building consumers are regular and non-technical clients of the buildings. They are generally not familiar with the construction cost of different types of wall materials, nor can they distinguish between the impacts of different types of materials on the building's energy consumption. Furthermore, a significant portion of the building envelope is covered when consumers visit the buildings for the first time. Concealed parts of the buildings attract less attention from the buyers compared to the visible parts. Therefore, the high cost of the concealed portions of the wall materials is barely paid off for the investors. In the current condition of the residential building market, these investors are not encouraged to change their approach in using low-cost and traditionally produced wall materials.

Based on the field observations, the use of traditional wall materials is also widespread among the second group of builders, i.e., builders who are ultimately going to occupy the building. To date, no prior research has been conducted to analyze the balance between the construction and the energy costs of the envelope materials in different parts of Iran. As a result, these builders are not knowledgeable regarding the cost balance of various building materials. Currently, guidelines provided by BHRC [37] are the primary reference for selecting energy-efficient materials. These guidelines, however, cover a limited number of wall materials. It only considers the energy performance but not the cost performance in its recommendations and follows the accept/reject approach for different materials. For example, among six different wall materials investigated in the research, BHRC [37] only covers two traditional wall materials included in Scenarios 1 and 2. Both these materials are accepted according to the BHRC [37] set criteria. Nevertheless, these two scenarios were identified with the lowest performance among the studied scenarios throughout the building's life cycle. Therefore, even in the cases where builders consider the concurrent energy and the cost performance of wall materials over the building's life cycle, no dependable source was available.

The current situation in the residential building construction market in the country can be changed when municipalities require the builders to reveal their envelope materials, e.g., in the building permits. Furthermore, municipalities need to research the high energy and the cost performance envelope materials in their regions. Presenting the impacts of different envelope materials, on the energy consumption of the building, to the building's consumers can further educate them. It can potentially increase the consumers' demands for the buildings with high cost and energy performance ratings. The increase in demand can hike the price of these buildings and motivate building developers to use high-performance envelope materials.

5. SUMMARY AND CONCLUSION

As the boundary between the interior and exterior of the building, the building envelope plays an essential role in the building's cost and energy performance over the building's life-cycle. This essential role has encouraged many researchers to investigate influential factors affecting the performance of the building envelope. The emergence of BIM in the recent decade has created an opportunity to facilitate the evaluation and improvement of the resulting performance of the building envelope. This research responded to the identified need for a structured method to guide practitioners in identifying the most viable building envelope materials within a region over the life cycle. The proposed method utilizes BIM capabilities to accurately capture detailed specifications of buildings, and evaluate the building's cost and energy performance considering influential regional factors. The sample implementation of the method in Tehran, Iran, indicated the current prevalent traditional wall materials are neither energy-efficient nor cost-efficient compared to the available industrial and semi-industrial wall materials. The proper selection of the building envelope materials, in this case, demonstrated a potential energy savings of 31% during the building's operation phase and the resulting envelope life cycle cost reduction of 28%. As a result of the sample implementation of the method, high-performance wall materials were identified for the building construction industry in Tehran. Furthermore, for the first time, prevalent building envelope materials used by building constructors in the city were identified.

Implementation of the proposed method in a region can benefit various stakeholders. Municipalities can use the method to identify and introduce a list of viable envelope materials to the builders as guidelines, or even instructions. The use of the recommended materials can increase the profit margin of the homebuilders. Building residents can see the benefits of their reduced utility bills. The entire society gains advantages due to reduced energy consumption and green gas emission. In this research, the embodied energy of the envelope materials was not directly taken into account. The implied cost of the embodied energy was assumed in the purchase cost of the envelope materials. Incorporating the embodied energy of the envelope materials can be considered in future research to improve the resulting energy performance of the envelope materials. In the financial assessment of the building, only direct construction and operation costs were considered. Other influential factors might play a vital role in the performance evaluation of the buildings. For example, in different envelope scenarios, the thickness of the walls was different. It is assumed that the thin walls result in more building space than the thick walls improving the performance of the buildings. The implication of the adopted wall thickness on the building performance was not considered in this study.

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Persian Abstract

چکیده

شرایط محیطی و ترکیب مصالح استفاده شده در پوشش بیرونی ساختمان‌ها نقش زیادی در میزان مصرف انرژی و هزینه‌های ساخت و نگهداری ساختمان دارد. با این حال هنوز روش‌های مدون و ساخت‌یافته‌ای که با در نظر گرفتن تأثیر شرایط محیطی و نوع مصالح مورد استفاده در پوشش بیرونی ساختمان، مناسب‌ترین ترکیب مصالح مصرفی در پوشش بیرونی ساختمان را شناسایی نمایند و سازندگان ساختمان را در این زمینه یاری نماید، ارائه نشده است. این مطالعه با ارائه یک روش نوین با استفاده از قابلیت های مدل سازی اطلاعات ساختمان، به این نیاز پاسخ می‌دهد. در این روش با در نظر گرفتن شرایط محیطی صنعت ساخت، شرایط آب و هوایی منطقه و همچنین در نظر گرفتن هندسه و ابعاد ساختمان، مصالح مورد استفاده در پوشش ساختمان که هم از منظر هزینه و هم از نظر مصرف انرژی در طول چرخه عمر ساختمان به صرفه هستند شناسایی و پیشنهاد می‌شوند. ابتدا مصالح مرسوم مورد استفاده در ساخت ساختمان‌ها در منطقه شناسایی می‌شوند، سپس عملکرد مصرف انرژی آنها با استفاده از قابلیت‌های ارائه شده در مدلسازی اطلاعات ساختمان شبیه سازی می‌شود و در نهایت هزینه چرخه عمر آنها ارزیابی می‌گردد. به منظور بررسی قابلیت‌های این روش، این روش برای ساخت ساختمان‌ها در شهر تهران اجرا شد و با موفقیت برای کاهش هزینه و مصرف انرژی در یک نمونه موردی ساختمان مسکونی نه طبقه استفاده شد. نتیجه استفاده از روش پیشنهادی در نمونه موردی، پیشنهاد استفاده از مصالح جایگزین به منظور کاهش مصرف انرژی به میزان ۳۱٪ و کاهش هزینه در چرخه عمر ساختمان به میزان ۲۸٪ بود. روش پیشنهادی می تواند با کاهش هزینه و مصرف انرژی ساختمان‌ها، ذینفعان مختلف در صنعت ساختمان سازی از جمله شهرداری ها ، مالکان ، پیمانکاران و مصرف کنندگان را بهره‌مند سازد.