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Building Energy Management Using Building Information Modeling: Evaluation of Building Components and Construction Materials

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ABSTRACT

Traditionally, building energy model is created in isolation from the architectural building information model and energy analyses have relied on a single analysis tool. The building energy model can be generated more quickly by leveraging existing data from the BIM. The impacts of energy consumption are significant in the building usage phase, which can last several decades. Due to the large share of the final energy consumption in the building sector, accurate analysis of thermal and cooling loads of a building and the efforts to reduce energy losses represent an effective way to reduce energy consumption. Therefore, it is essential to analyze the building energy performance in the design phase, which is when critical decisions are made. This study aims to investigate the impact of the building components and construction materials on building energy efficiency using Building Information Modeling (BIM) technology in a mild climate zone. After reviewing the proposed designs, the main building form was chosen for energy modeling and analysis. Then, building energy consumption analysis was performed based on the basic parameters of the building energy model. Eventually, the most optimal mode was selected by examining different energy consumption forms. This study showed that the building HVAC system always had the largest share of energy consumption. Finally, the results of parametric studies on alternative schemes of energy use intensity optimization showed that 22.59 % savings could be achieved as compared to the base building model in a 30-year time horizon.

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1. INTRODUCTION

Buildings are the world's largest energy consumer, according to the United Nations Environment Program [1]. Residential energy consumption has allocated a large percentage of national energy consumption to itself in most countries [2]. Recently, global efforts have been directed at reducing carbon emissions from buildings [3]. Operational energy reduction has been the main focus of the industry because it accounts for a greater proportion of carbon emission throughout the building lifecycle and it is easier to predict than embodied energy [4]. Usually, following the architectural plans and considering construction documents, the building performance analysis should be done [5]. Analyzing the energy performance of a building in its early design stage requires access to specific information such as properties of materials, U-value, and technical systems. Such information is one of the determinants of building energy performance [6]. The geometric information of buildings is usually extracted from architectural drawings. Then, an energy analyst can benefit from this information to define the building's thermal view, which depends on its knowledge, skills, and experience. Therefore, various building energy analysts will generate differing thermal views [5]. BIM is a technology used for improving productivity and efficiency in the construction industry [7]. A data model created by integrating 3D digital techniques and specific information related to an engineering project is the best description for building information modeling [1]. One of the most significant benefits of BIM lies both in early-stage design and later stages of building energy simulation analysis [8]. Application of BIM in Energy Performance Assessment (EPAs) considerably reduces time and costs [7]. The limitation of energy resources and the significant growth of using them in Iran compared with the worldwide average have doubled the necessity of optimizing energy consumption in this country [9]. According to the information provided in 2016, the share of building fuel consumption is about 41.4 % of the total energy consumption in the country, which is considered the largest energy consumer sector [10]. Due to the high share of energy consumption in this sector, accurate analysis of thermal and cooling loads of a building and the efforts to reduce energy losses represent an effective way of reducing energy consumption. Building Information Modeling enables information sharing and reuses for interoperability between popular software packages in Architecture, Engineering, and Construction industry. BIM-based energy simulation can significantly reduce the costs and time required to create a geometric model [11]. Many different studies have employed BIM technology in the field of building energy management.

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Based on previous studies from the famous database [12-28], it can be concluded that there is a limited body of research on energy efficiency using the simultaneous evaluation of building components and construction materials using Building Information Modeling (BIM) technology. In other words, all related studies were focused on a specific component and there was not any research that had simultaneously investigated the impact of all involved components on energy consumption. This paper carries out energy performance assessment based on BIM technology. The results indicate that the use of BIM technology will lead to design identification, comparison, and reduction of energy consumption in the early stages of design.

2. METHOD

2.1. Methodology

In this study, to examine different design ideas, several conceptual masses were created using Autodesk Revit software with a top-down design approach. The main form of the building for energy modeling and analysis was selected only after reviewing the proposed designs. Then, an exact model of building elements was fabricated. After generating the energy model, the building energy consumption analysis was carried out based on basic parameters. Finally, the most optimal mode was selected by examining different energy consumption forms.

2.2. Case study

The case study is a residential building that is located in a mild climate in Rasht, Iran. The total area of the building is about 101000 m^2 and the project location is in Rasht, Gilan province, Iran (37°18'34.8"N, 49°36'49.0"E). At first, several conceptual masses were created to study different design ideas. The closest form to the real model of the building and items such as the number of units and the area of the building were considered in the construction of conceptual models. Input parameters of the energy model were selected according to the software defaults (as shown in Table 2). Table 1 shows the comparison of different building forms based on the simulation of energy consumption in conceptual masses. After reviewing the proposed designs and creating a real model of the building, an energy analysis was performed. Carrying out the whole building energy analysis is not possible in the cloud due to the software limitation in sending the shade surfaces (max. 10000 surfaces) as well as the number of doors (max. 4096 doors). For this reason, as shown in Figure 1, each block of this residential tower is analyzed separately. Finally, due to increased shade surfaces, the ceiling elements were removed from the building model. The samples of the second-floor plan and penthouse plan are separated by unit type, as shown in Figure 2.

The results of the analysis show that the first form of the building has the lowest energy consumption among others. The cost of energy consumption based on Table 2 parameters is 13.5 USD/m^2/year. Accordingly, the energy use intensity is equal to 110 kWh/m^2/year, as shown in Table 1. In this form, the building orientation is based on the geographical north. Thus, the angle of the building is automatically determined by the software based on the building form and the geographic coordinates of the project. The window-to-wall ratio in all directions is 40 % by default. All windows have shades with a depth of 45.72 cm. Also, the type of windows in the conceptual model is double-glazed windows without any external coating. The structure of walls in the conceptual model in the form of lightweight walls with typical mild climate insulation and the roof structure is lightweight without insulation. The values of the building infiltration rate, the lighting efficiency, the plug load efficiency, and the operating schedule are adjusted according to the BIM parameter (as shown in Table 2). The building's HVAC system is assumed to have a BIM parameter (Residential 14 SEER/0.9 AFUE Split/Packaged Gas <5.5 ton). This building has no daylighting and occupancy controls system and photovoltaic solar panels. After adjusting the effective parameters for energy consumption, according to Table 3, the energy cost would be 5.71 USD/m^2/year. Accordingly, the energy use intensity would be equal to 75.3 kWh/m^2/year. The building orientation remains unchanged relative to the previous model (base model) and is based on the geographical north. The window's ratio to the northern and southern walls is 40 % by default. These windows have shades as high as 2/3 of the window height. Also, the type of these windows in the conceptual model is triple-glazed windows with low emission. Due to the lack of significant efficiency, the eastern and western windows have been removed from the conceptual model. The structure of walls in the conceptual model is according to Table 2 and the roof structure is lightweight without insulation. The value of the building infiltration rate is 0.17 ACH. The value of the lighting efficiency parameter is assumed to be 3.23 W/m^2. The values of the plug load efficiency and the operating schedule were adjusted according to the BIM parameter. The building's HVAC system is assumed to be a high-efficiency variable air volume system. Also, the building has a daylighting and occupancy control system. Finally, to achieve the highest level of energy efficiency, photovoltaic solar panels were used. To this end, the photovoltaic solar panels were used with a yield of 20.4 % and surface coverage of 90 %. The payback limit of these panels was selected for 30 years. The results of this analysis show that the use of building information modeling technology for adjusting the parameters affecting energy consumption in the conceptual designs can save up to 57.7 % in energy cost. Based on the energy use intensity, this value would be 31.54 %.

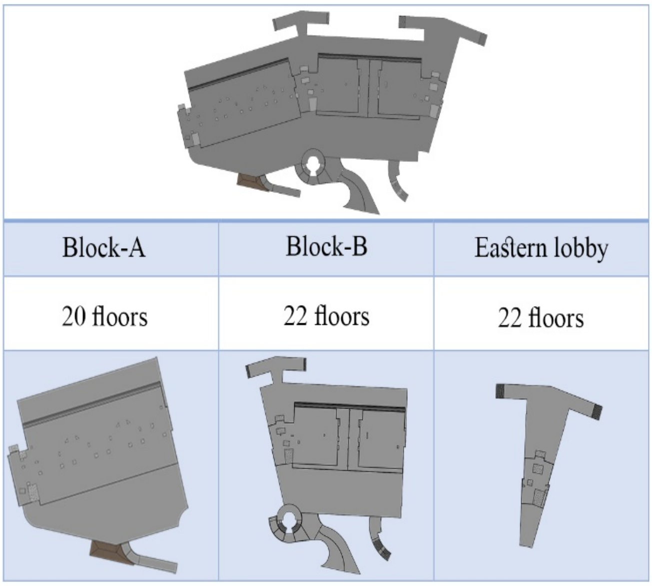

Figure 1. Separation of building blocks for energy analysis

Figure 2. Top left) A sample of the second-floor plan (Block A); Top right) A sample of the penthouse first-floor plan (Block B); Bottom left) A sample of the second-floor plan (Block B); Bottom right) A sample of the penthouse second-floor plan (Block B)

Table 1. Comparison of different building forms in conceptual masses

		Module-1	**Module-2**	**Module-3**
	Floors	22	43	43
	Units	548	560	561
	Height (m)	81.70	159.40	159.40

Building form		**Energy cost** (USD/m^2/year)	**Saving** (%)	**Energy use intensity** (kWh/m^2/year)	**Saving** (%)
Module-1	BIM parameters	13.50	0	110	0
	Optimized parameters	5.71	57.70	75.30	31.54
Module-2	BIM parameters	14.10	0	115	0
	Optimized parameters	7.45	47.16	92.10	19.91
Module-3	BIM parameters	13.90	0	114	0
	Optimized parameters	7.24	47.91	88.10	22.72

Table 2. Basic and optimized parameters based on energy consumption simulation in conceptual masses

Building form	**Module-1**		**Module-2**		**Module-3**	
Energy cost (USD/m^2/year)	13.5*	5.71**	14.1*	7.45**	13.9*	7.24**
Effective factor	Input parameter					
Building orientation	BIM°					
WWR (South)	BIM (40 %)°					
Window shades	BIM (0.4572 m)*					
	2/3 Win height**					
Window glass	BIM (Double pane clear-No coating)*					
	Trp LoE**					
WWR (North)	BIM (40 %)°					
Window shades	BIM (0.4572 m)*					
	2/3 Win height**					
Window glass	BIM (Double pane clear-No coating)*					
	Trp LoE**					
WWR (West)	BIM (40 %)*					
	(0 %)**					
Window shades	BIM (0.4572 m)*					
	BIM (No shade)**					
Window glass	BIM (Double pane clear-No coating)*					
	BIM (No window)**					
WWR (East)	BIM (40 %)*					
	(0 %)**					
Window shades	BIM (0.4572 m)*					
	BIM (No shade)**					

Window glass	BIM (Double pane clear-No coating)*
	BIM (No window)**
Wall construction	BIM (Lightweight construction-Typical mild climate insulation)*
	R13+R10 Metal**
Roof construction	BIM (Lightweight construction-No insulation)°
Infiltration	BIM (None)*
	0.17 ACH**
Lighting efficiency	BIM (10.76 W/m^2)*
	3.23 W/m^2**
Daylighting and occupancy controls	None*
	Daylighting & occupancy controls**
Plug load efficiency	BIM (10.76 W/m^2)°
HVAC	BIM*
	High Eff. VAV**
Operating schedule	BIM (24 Hours)°
Panel efficiency (PV)	None*
	20.4 %**
Payback limit (PV)	None*
	30 years**
Surface coverage (PV)	0 %*
	90 %**
*Base Model, **Optimized, °Unchanged	

The building energy model requires a group of parameters depending on the analysis tools and specific studies. Table 3 shows the basic parameters of the building energy model as the basis of design. These parameters include HVAC, materials with thermal properties, plug loads, building occupancy, building natural infiltration rate, lighting density and efficiency, natural ventilation, internal heat gains (plug loads and occupancy), thermostat set-point temperatures, and operating schedules. These parameters are specified by the BIM title in the provided data.

Table 3. Basic parameters of the building energy model

Input parameter	**Value**
HVAC system	Residential 14 SEER/0.9 AFUE Split/Packaged Gaz < 5.5 ton
Area per person	105.82 m^2
Sensible heat gain (per person)	73.27 W
Latent heat gain (per person)	58.61 W
Power load density	10.76 W/m^2
Lighting load density	10.76 W/m^2
Plenum lighting contribution	20 %
Occupancy schedule	24 Hours
Lighting schedule	All day
Power schedule	All day
Outdoor air (per person)	2.36 L/s
Outdoor air (per area)	0.30 L/ (s.m^2)
Unoccupied cooling set point	27.78 °C
Infiltration (ac/h)	None
Fabric *U*-values	
External walls	20 cm concrete block (*U*-value 6.5 W/m^{2}K)
Internal walls	10 cm concrete block (*U*-value 13 W/m^{2}K)
Shear walls	45 cm reinforced concrete (*U*-value 2.3244 W/m^{2}K)
Floor	22.5 cm concrete slab (*U*-value 4.6489 W/m^{2}K)
External doors	Wooden, Single-Flush (*U*-value 2.1944 W/m^{2}K)
Terrace doors	Wood frame with single clear glass (*U*-value 5.6212 W/m^{2}K)
Lobby doors	Metal frame with single clear glass (*U*-value 6.5580 W/m^{2}K)
Elevator doors	Metal (*U*-value 3.7021 W/m^{2}K)
Windows	1/8 in Pilkington single glazing (*U*-value 3.6886 W/m^{2}K)

2.3. Climate data

Climate data are automatically taken from the nearest meteorological station database after the energy model sending as the first element of the environment in which the building is located (Table 4). This information is related to the project location, which is available in the Autodesk Green Building Studio (GBS) software database, and the distance specified in Table 4 is only the storage of data at the desired station. Data on design conditions based on dry-bulb temperature and Mean Coincident Wet Bulb (MCWB) temperature are shown annually in Table 5. Also, Figure 3 shows the average daily minimum and maximum temperature basis on monthly data.

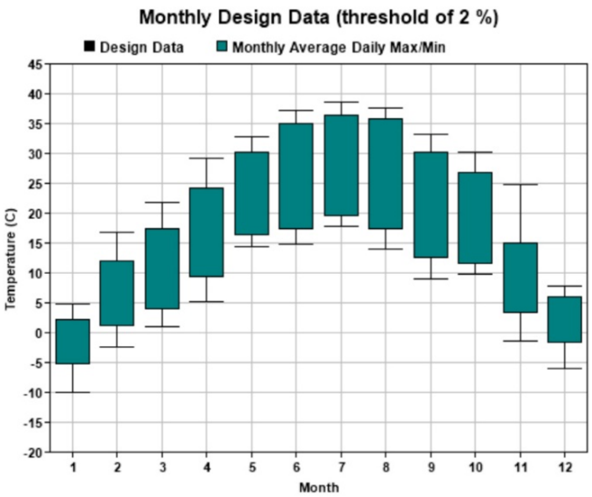

Figure 3. Average of Max. and Min. daily temperatures on a monthly basis [29]

Table 4. Receiving the temperature data from the nearest weather station database by Autodesk Green Building Studio software

Weather station: GBS_06M12_12_002300 Distance to project 474.2 mi (763.2 km) Latitude=36.4167, Longitude=58.1500			Unit: SI
Cooling degree day		**Heating degree day**	
Threshold	Value	Threshold	Value
18.3 °C	1110	18.3 °C	2047
21.1 °C	657	15.6 °C	1577
23.9 °C	316	12.8 °C	1172
26.7 °C	104	10 °C	807

Table 5. The dry-bulb and Mean Coincident Wet Bulb temperature based on annual data

Annual design conditions				Unit: SI
Threshold	**Cooling**		**Heating**	
	Dry bulb (°C)	MCWB (°C)	Dry bulb (°C)	MCWB (°C)
0.1 %	39.2	18.1	-10.4	-11.3
0.2 %	38.8	17.9	-9.8	-11.0
0.4 %	38.4	17.9	-9.2	-10.4
0.5 %	38.2	18.0	-8.8	-9.8
1 %	37.3	17.3	-7.6	-8.9
2 %	36.4	16.9	-4.8	-6.5
2.5 %	36.0	16.7	-3.9	-5.7
5 %	34.1	15.8	-1.9	-3.7

2.4. Solar orientation study

This study investigates solar radiation on building surfaces. After setting parameters such as project location, date, time, and time interval, a graphical illustration of solar radiation is given (Figure 4). This study shows that block A (located on the western side of the site) with much sunlight received during a day has a better position than block B.

3. DATA ANALYSIS

After modeling and adjusting the parameters required in Autodesk Revit software (Table 3), an energy model was made using the analysis tab. Then, to send the energy model and receive the data analysis results, an Autodesk account was used. It should be noted that by sending the energy model through the Autodesk Revit software to the Autodesk Insight software, an energy model will be sent to the Autodesk Green Building Studio software. Also, this software could be used to validate the results of energy analysis.

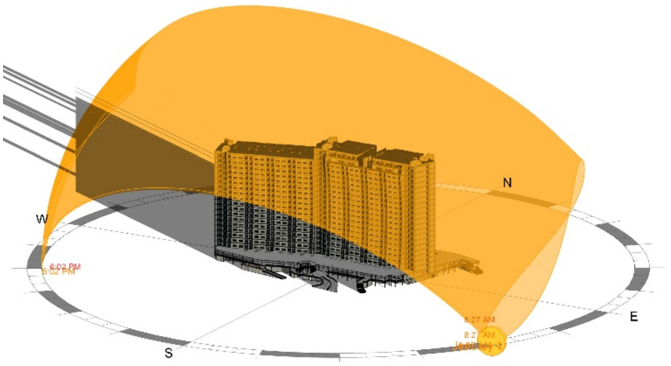

Figure 4. Sunlight radiation on building surfaces

Investigation of the charts of Figure 5 for block A shows that the highest energy cost is in July. According to this analysis, ventilation fans and space cooling have the highest share among all other affecting parameters for energy consumption. Also, the maximum energy use intensity of block A is in January, as shown in Figure 6. The space heat and ventilation fans have had the largest share among other parameters. Accordingly, the highest level of energy consumption based on energy cost is in July and August and energy use intensity is in January and December. The schematic diagrams of energy consumption for block B and the eastern lobby are similar.

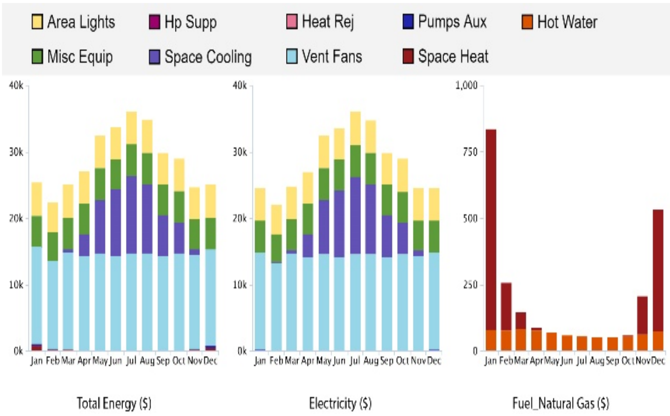

Figure 5. Energy consumption index based on energy cost, Block A

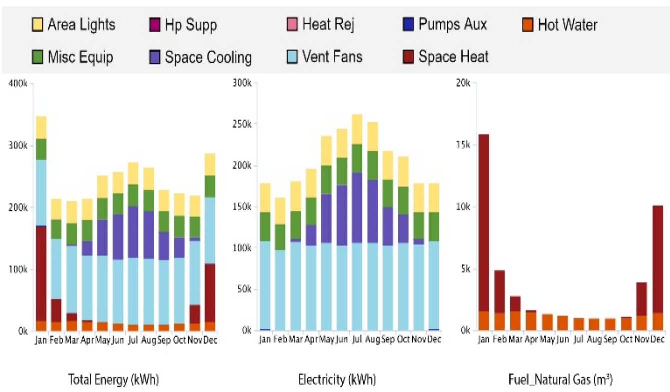

Figure 6. Energy consumption index based on energy use intensity, Block A

4. DISCUSSION

The results of the analysis show that block A has the lowest energy consumption. The cost of energy consumption based on the parameters in Table 7 is 13 USD/m^2/year, as shown in Table 6. This value for block B and the eastern lobby is 13 and 14.1, respectively. Accordingly, the energy use intensity for blocks A, B, and the eastern lobby will be equal to 112, 119, and 191 kWh/m^2/year, respectively. The building orientation, in this case, is based on the geographical north. Thus, the angle of the building is automatically determined by software based on the building form and the project geographic coordinates. The ratios of the window to the northern, southern, eastern and western walls are 16 %, 20 %, 7 %, and 5 %, respectively. The ratio values for blocks B are: 18 %, 22 %, 9 %, and 7 % and for the eastern lobby 15 %, 25 %, 13 %, and 14 %. The shades of all windows are considered by default. Therefore, the windows installed on the terraces use their overhead ceiling as shade. Other windows installed on the surfaces of external walls lacked a shading system. Also, the type of windows was based on the element defined in Autodesk Revit software (as shown in Table 7). The walls and roof structures are shown in Tables 3 and 7. The values of building infiltration rate, lighting efficiency, plug load efficiency, operating schedule, and building's HVAC system were adjusted according to the BIM parameter (as shown in Table 7). This building has no daylighting and occupancy controls system and photovoltaic solar panels. According to Table 7, after adjusting the effective parameters for energy consumption, the energy cost of block A is determined at 5.4 USD/m^2/year. This value for block B and the eastern lobby is 6.47 and 8.03, respectively. Accordingly, the energy use intensity for blocks A, B, and the eastern lobby will be equal to 86.7, 99, and 170 kWh/m^2/year, respectively. The building orientation in comparison to the previous base model remains unchanged based on the geographical north. The window's ratio to the northern and southern walls is unchanged and equal to 16 % and 20 % for block A; 18 % and 22 % for block B; 15 % and 25 % for the eastern lobby, respectively. The northern window shades were considered by default, for all blocks. Also, the southern window shades are selected as high as 2/3 of the window height. As shown in Table 7, the type of northern windows was unchanged for all blocks. The type of southern window is of triple-glazed one with low emission. Due to insignificant efficiency, the eastern and western windows were removed from the building model. The walls and roof structure are shown in Table 7. The value of the building infiltration rate is 0.17 ACH. The value of the lighting efficiency parameter is assumed to be 3.23 W/m^2. The values of plug load efficiency and operating schedules were adjusted according to the BIM parameter. The building's HVAC system was assumed to be a high-efficiency variable air volume system. Also, the building has a daylighting and occupancy control system. Finally, to achieve the highest level of energy efficiency, photovoltaic solar panels were used. For this purpose, the photovoltaic solar panels were used with a yield of 20.4 % and surface coverage of 90 %. The payback limit of photovoltaic panels in Autodesk Insight software is in 10-year, 20-year, and 30-year periods. Considering the arrangement of other parameters affecting energy consumption and related analysis showed that the time period between 20 and 30 years would not affect the output results. Therefore, the payback limit of these panels was considered for 30 years. The results of this analysis showed that the use of building information modeling technology in the adjustment of effective energy consumption parameters could save up to 58.46 % in energy cost for block A. This value for block B and the eastern lobby is 50.23 % and 43.05 %, respectively. Based on this result, this value based on the energy use intensity for blocks A, B, and the eastern lobby is 22.59 %, 16.81 %, and 11 %, respectively.

Table 6. Investigation and comparison of different energy consumption scenarios in building blocks

Building block		**Energy cost** (USD/m^2/year)	**Saving** (%)	**Energy use intensity** (kWh/m^2/year)	**Saving** (%)
A	BIM parameters	13	0	112	0
	Optimized parameters	5.40	58.46	86.70	22.59
B	BIM parameters	13	0	119	0
	Optimized parameters	6.47	50.23	99	16.81
Eastern lobby	BIM parameters	14.10	0	191	0
	Optimized parameters	8.03	43.05	170	11

Table 7. Basic and optimized parameters for building energy consumption

Building block	**Block A**		**Block B**		**Eastern lobby**	
Energy cost (USD/m^2/year)	13[*]	5.40[**]	13[*]	6.47[**]	14.1[*]	8.03[**]
Effective factor	Input parameter					
Building orientation	BIM[°]					
WWR (South)	BIM (20 %)[°]		BIM (22 %)[°]		BIM (25 %)[°]	
Window shades	BIM[*]					
	2/3 Win height[**]					
Window glass	BIM (Sgl Clr)[*]					
	Trp LoE[**]					
WWR (North)	BIM (16 %)[°]		BIM (18 %)[°]		BIM (15 %)[°]	
Window shades	BIM[°]					
Window glass	BIM (Sgl Clr)[°]					
WWR (West)	BIM (5 %)[*]	(0 %)[**]	BIM (7 %)[*]	(0 %)[**]	BIM (14 %)[*]	(0 %)[**]

Window shades	BIM*					
	BIM (No Shade)**					
Window glass	BIM (Sgl Clr)*					
	BIM (No Window)**					
WWR (East)	BIM (7 %)*	(0 %)**	BIM (9 %)*	(0 %)**	BIM (13 %)*	(0 %)**
Window shades	BIM*					
	BIM (No shade)**					
Window glass	BIM (Sgl Clr)*					
	BIM (No window)**					
Wall construction	BIM (Concrete masonry units)*					
	R13+R10 Metal**					
Roof construction	BIM (Concrete, Cast in situ)$^{\circ}$					
Infiltration	BIM (None)*					
	0.17 ACH**					
Lighting efficiency	BIM (10.76 W/m^{2})*					
	3.23 W/m^{2**}					
Daylighting and occupancy controls	None*					
	Daylighting & occupancy controls**					
Plug load efficiency	BIM (10.76 W/m^{2})$^{\circ}$					
HVAC	BIM*					
	High Eff. VAV**					
Operating schedule	BIM (24 Hours)$^{\circ}$					
Panel efficiency (PV)	None*					
	20.4 %**					
Payback limit (PV)	None*					
	30 years**					
Surface coverage (PV)	0 %*					
	90 %**					
*Base Model, **Optimized, $^{\circ}$Unchanged						

It should be noted that this study was performed to convince the employer of the worth and benefit of BIM technology in optimizing energy consumption in a real project. As mentioned, due to the software limitations in sending the energy model, the building blocks were divided and also the ceiling elements were removed from the building model. Thus, the thermal height on the first and other floors was 4 m and 3.7 m, respectively. This building could have lower energy consumption than the values obtained in this analysis due to the implementation of the ceiling elements during the construction phase and reduced computational height of the spaces as a result. However, the results of this analysis show that block A has the lowest energy consumption. Considering the similar materials and equipment, this is due to the building orientation with the actual north of the region (geographic north). Accordingly, with the implementation of block B along the block A, the lowest energy consumption resulting from the maximum solar radiation during a day can be achieved. Also, this study shows that the results of the conceptual model analysis are more acceptable than the results of the actual building model. It can be useful in the early stages of decision-making for the project.

5. CONCLUSIONS

To investigate different design ideas, several conceptual masses were created in Autodesk Revit software. Next, the main form of the building was chosen only after reviewing the proposed designs in terms of energy cost as well as considerations such as project location, site scope, building height, facilities, and project cost. Then, an exact model of the building elements was created in Autodesk Revit software. Finally, after generating and analyzing the energy model, the most optimal mode was selected by examining different forms of energy consumption. The results of this analysis showed that the use of building information modeling technology in adjusting the affected energy consumption parameters would save up to 58.46 % in energy cost for block A, compared to the base building model in a 30-year time horizon. This value was 50.23 % for block B and 43.05 % for the eastern lobby. As a result, this value would be 22.59 %, 16.81 %, and 11 % for blocks A, B, and the eastern lobby, respectively, based on the energy use intensity. The results of this study showed that the use of Building Information Modeling (BIM) technology in optimizing the building energy consumption could significantly save energy costs. Also, the results of this study showed that the building HVAC system always had the highest share of energy consumption. Therefore, choosing the right type of HVAC system could achieve the lowest level of energy consumption in the building.

6. ACKNOWLEDGEMENT

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NOMENCLATURE

ACH	Air Changes per Hour
AFUE	Annual Fuel Utilization Efficiency
BIM	Building Information Modeling
Clr	Clear

Eff	Efficiency
HVAC	Heating, Ventilation, and Air Conditioning
LoE	Low Emissivity
PV	Photovoltaics
R13+R10	Construction material
SEER	Seasonal Energy Efficiency Ratio
Sgl	Single
Trp	Triple
VAV	Variable Air Volume
WWR	Window-to-Wall Ratio

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