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SUSTAINABLE BUILDING DESIGN IN COLD CLIMATE REGION: A FRAMEWORK FOR RESIDENTIAL BUILDING

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Abstract: The need for sustainable buildings has become more evident to curb the building's environmental footprint through passive designs, and efficient utilization of energy and materials. The aim of this study is to investigate the impact of building form, orientation, shading, and building envelope on energy consumption/cost of a residential building. Building information modeling (BIM) using Revit 2017 and associated Green Building Studio (GBS) are utilized for the design process. In the first step of the proposed methodology, three forms of low-rise buildings, designed for cold climate, are investigated to study their energy consumption. The model with most efficient energy performance has been adopted for further analyses. Next, sensitivity analysis is performed where several test scenarios are conducted to measure the impact of different sustainable features on energy use. Results for the study cases show that the building envelope had a greater impact with energy saving of 45.43%, 19.8%, 13.4%, and 30% by utilizing window-wall-ratios (WWR) 15%, window type "triple glazing low-e", wall insulation R-value 44, and roof insulation R-value 60 respectively. Likewise building form reduced energy consumption significantly by 38.2%. As such, shading reduced energy by 6.25%. Further improvement in energy performance has been achieved by encompassing orientation +90° east north of south and WWR of 27%. The total saving in the peak monthly electricity and fuel consumption is 4.1 KW, 39 GJ, respectively. Furthermore, the saving in net CO_2 emission is 10 tons/year and the total reduction in the lifecycle cost is $48,897.

Keywords: building information modelling, sustainability, energy simulation, building envelope

1 INTRODUCTION

Buildings around the globe are responsible for approximately, 19% CO_2 emissions and 32% of the total energy consumption (Abanda and Byers 2016). However, through sustainable design there is significant room to reduce the energy demand by buildings thereby reducing the carbon dioxide emissions (Lechner 2014). In practice, there are various factors that can affect and positively control building energy use. For instance, building envelope components such as windows, roofs and external walls have a significant impact on building's energy performance and can play a vital role in determining the internal energy demand (LaFrance et al. 2013). Many design options are available to achieve sustainability requirements, which reduce energy consumption and subsequently the carbon footprint. Addressing climate responsive design, in the design process, requires determining the impact of various environmental factors such as wind, rain, temperature and humidity (Hyde 2013). In cold climate weather, such as Toronto, protection from cold winters and humid summers are considered some of the main climate responsive design strategies. Studies have proposed that improved insulation remarkably reduces energy consumption (Caldera, Corgnati, and Filippi 2008). The size and shape of a building should be taken into account in energy consumption (Catalina, Virgone, and Iordache 2011). Building orientation can reduce energy demands considerably; a better orientation can enhance solar contribution (Carbonari, Rossi, and Romagnoni 2002). In the light of the previously mentioned factors, the emergence of BIM has developed to provide an outstanding integration platform that can overcome the various challenges during design and service life of the building. The major advantage of such solutions is the ability to virtually analyze the impacts of different aspects on building energy at the design process by different professionals simultaneously. This gives the stakeholders to work in an integrated manner and provide the opportunity to perform any alterations before a single brick of the building construction is placed on site (Bryde, Broquetas, and Volm 2013) and continue to be useful as the building is constructed and operated. This project attempts to design sustainable building for a target region. In this regard, Toronto, Ontario is considered. BIM tools will be utilized to investigate the impact of building envelope and other parameters on energy use. To achieve this objective, Revit 2017 (Kim, Kirby, and Krygiel 2017) was utilized to model three residential building forms, as well as to perform the initial energy analysis. Next, GBS (Azhar, Brown, and Farooqui 2009) has been used for sensitivity analysis of energy use by the buildings. In the last step, various building envelopes were adopted and investigated to acquire the optimal energy performance of all buildings. Various studies have designated the importance of adopting sustainability features in building constructions. In related work, (Aksoy and Inalli 2006) argued that acquiring an optimal building shape and orientation can save energy consumption up to 36%. A study was conducted (Poirazis, Blomsterberg, and Wall 2008) to analyze the influence of the building orientation, shading, and WWR between 30% and 100%. The study was performed on office buildings and obtained results reveal that the orientation has a slight influence on energy use. Increasing windows size is not a key factor in reducing lighting consumption and shading can reduce the cooling load efficiently. Another study was conducted to explore the best energy saving among various sustainable features (Tzempelikos, Athienitis, and Karava 2007). It has been found that optimal energy saving can be accomplished with an optimum combination of electric lighting systems, shading devices, and glazing. BIM and 3D-CAD were utilized (Stumpf, Kim, and Jenicek 2009) to explore different solutions in energy saving. Authors show that utilizing BIM in the early design process facilitates energy simulations among the project team members. Likewise, The feasibility of sustainability analyses based on BIM was examined in another study (Azhar and Brown 2009). The process includes three objectives: 1) identify the current state and the advantages of performing sustainability analysis on BIM. 2) explore several building performance analyses software. 3) develop a theoretical framework, through the project lifecycle, to explain the utilization of BIM for sustainability analysis. In the same context, BIM was utilized (Azhar et al. 2011) for designing buildings with sustainable features and used to generate Leadership in Energy and Environmental Design (LEED®) documentation. Results confirmed that this process could facilitate the LEED® certification procedure, as well as significantly reduce time. The main contribution of this paper is listed as follows:

- Develop a building sustainable framework using BIM.
- Conduct a parametric study on residential buildings using the developed framework to assist the effect of different building envelop parameters on energy consumption.
- Explore state-of-the-art energy simulation utilizing Revit 2017 and GBS tools.

2 RESEARCH METHODOLOGY

The framework of this study is demonstrated in Figure 1. At the initial step, an extensive literature review is conducted. In this context, various methods are reviewed in the field of BIM and energy simulation to choose the tools that suit the purpose of this project. Accordingly, BIM (Revit 2017) and energy simulation tools (Green Building Studio – GBS) are used to establish the models and to investigate the energy consumption, respectively. This process is performed on three building forms to study their energy use. Based on the obtained results, model with highest energy efficiency is considered for further analysis, to assess the impact of its envelope parameters on the energy consumption. Figure 2 demonstrates the three building forms, which includes 2-storey buildings and one bungalow. The Revit model will be exported to gbXML file and then imported into the green building studio -- GBS -- to conduct the sensitivity analysis. Several simulations are performed to measure the impact of building orientation, shading, windows to wall ratio, windows type, wall materials, and roof materials on the energy use. More precisely, the orientation scenarios will be investigated with clockwise increments, each +15°, from the base run (model natural position 0°angel with the north). Similarly, counter clockwise increments will be performed to explore other test scenarios. The shading depth and its effect on energy use will be examined to reduce cooling load during warm weather. Deciduous trees will be used on the landscape as they provide natural shading during summer and allows for daylight to access the building during the winter. To study the impact of building envelope on the energy consumption, a series of test cases will be conducted to determine the effect of WWR from 15% to 95%. Furthermore, the influence of the thermophysical properties of the building envelop has been evaluated. Ten windows types have been chosen for this study including: Type 1: Monolithic Clear Low-e, Type 2: Insulated Clear Low-e, Type 3: Insulated Green Low-e, Type 4: Insulated Blue Low-e, Type 5: Insulated Grey Low-e, Type 6: Triple Glazing Low-e, Type 7: Insulated Blue Reflective Low-e, Type 8: Insulated Green Reflective Low-e, Type 9: Insulated Grey Reflective Low-e, and Type 10: Insulated 3-pane Clear Low-e. In a similar manner, different test cases are conducted to assess the effects the wall and roof materials in terms of thermal resistance. Finally, building models are examined using Autodesk Insight A360 (Stine 2015) to study the effects of the entire envelope components on the energy consumption.

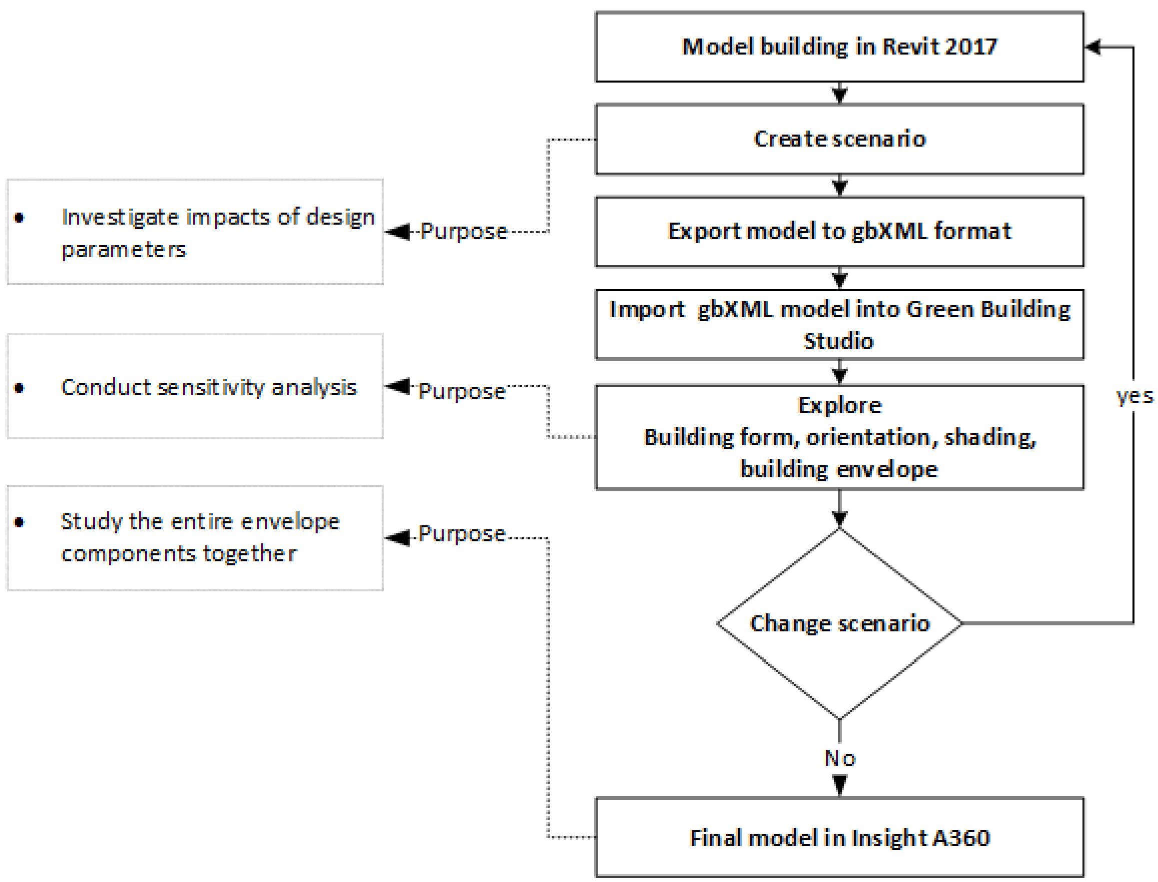

Figure 1: Research methodology

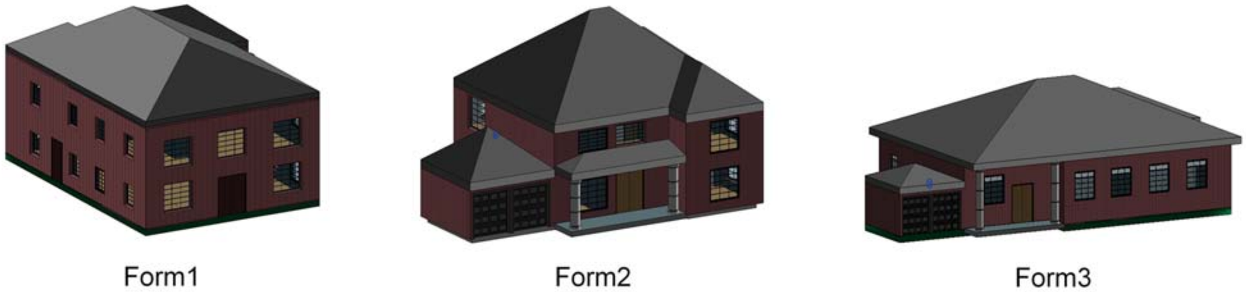

Figure 2: Building forms

3 RESULTS, ANALYSIS AND DISCUSSIONS

The following subsections present building energy performance details with respect to different aspects including the relationship between the energy consumption/cost and building form, shading, orientation, and building envelope. The assumptions made in Revit for the total lifecycle of the building is 30 years.

3.1 The Impact of Building Form on Energy Use/Cost

Building form is considered an essential parameter for passively designed buildings. To assess the relationship between the building configuration and climate, energy models have been constructed and examined for the three forms. Figure 3, demonstrates the comparison of estimated monthly fuel and electricity consumption of the three building forms.

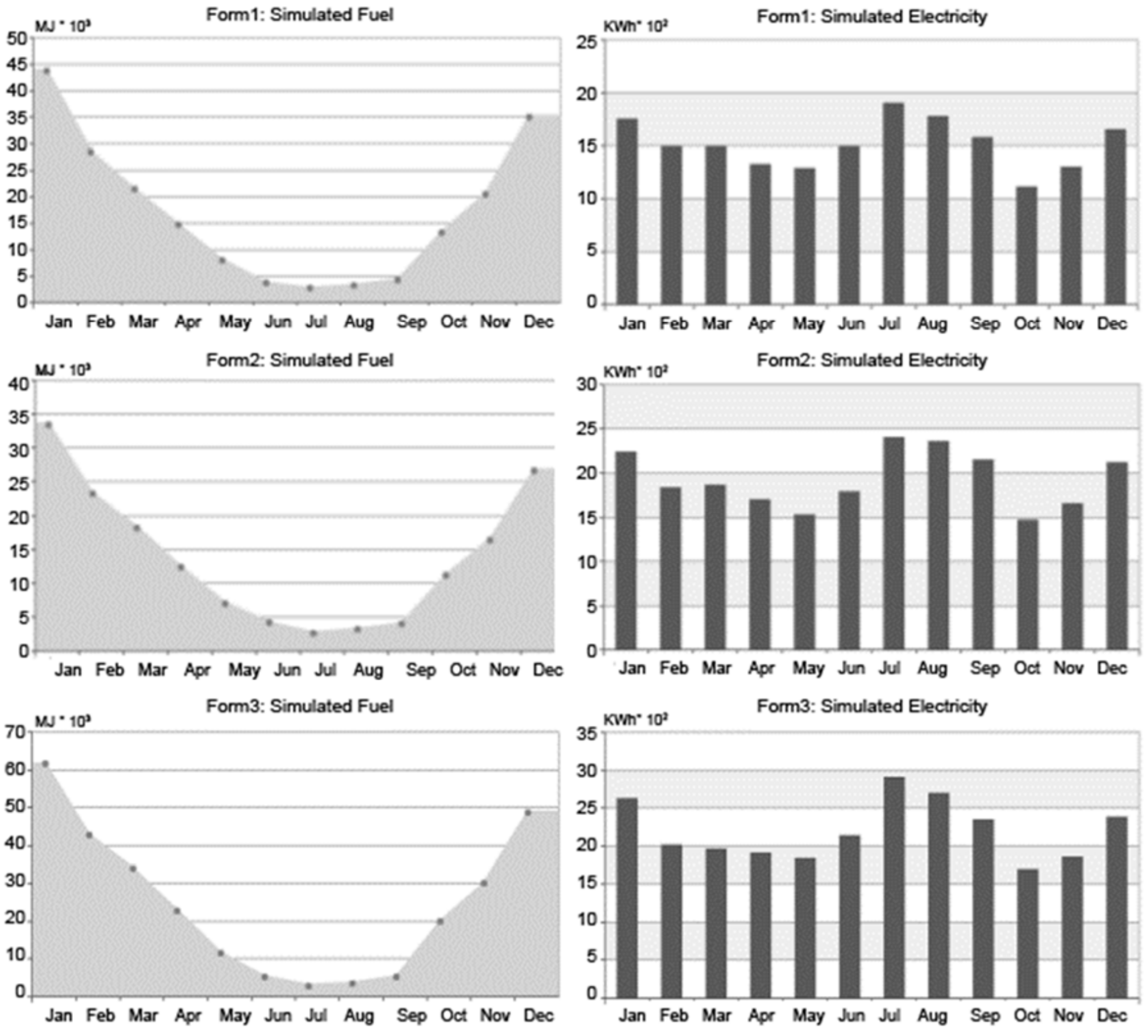

Figure 3: Monthly fuel and electricity consumption

According to the figure, form2 is expected to yield the minimum energy cost during the lifecycle. Furthermore, the peak periods of fuel and electricity consumption were in January (33,000MJ) and July(1,800KWh) respectively. In contrast, building form3 considered inefficient form as it is expected to have the highest fuel and electricity consumption during the peak periods at fuel value (62,000MJ) in January, and (2,800KWh) in July for the electricity. The variance in energy consumption occurs due to the compactness and windows distribution of the building. Hence, building form2 has acquired the better shape factor which reduces heat losses, save 38.2% of energy consumption, and obtain the lowest impact on the environment with net CO_2 emissions 8 metric tons/year, see Figure 4. In the light of such results, this form was selected to conduct detailed energy analysis.

3.2 The Impact of Building Orientation on Energy Use/Cost

Although the orientation of the building with respect to the sun radiation can affect the energy use by increasing/decreasing solar gain. The results in the present study case did not show significant variations. After considering different orientations to monitor the energy consumption of the building. In the first attempt (base run), the building was positioned 0 angle towards north direction. Next, several orientations were investigated between the angels -150 to +180. Table 1 shows the optimal building orientation led to 2.2% reduction of total lifecycle cost at angel +60° from the north. This orientation increases the building ability to heat gain through its envelop as well as allows more daylighting to access the inner space of the building. Consequently, the electrical energy used for lighting will be reduced. It is believed that if more aspect ratios and variables window/wall ratios etc. are used, the impact of orientation could be significant.

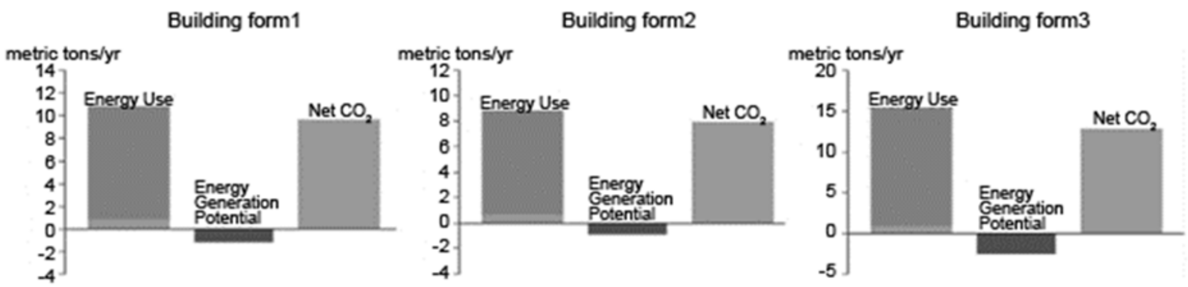

Figure 4: Annual carbon emissions

Table 1: Orientation impact on energy use/cost

Test no.	Run Name	Energy Use Intensity (MJ/m²/ yr)	Total Annual Cost			Total Annual Energy		
			Electric	Fuel	Energy	Electric (kWh)	Fuel (MJ)	Carbon Emissions (Mg)
1	0	1,190	$1,697	$1,874	$3,571	18,174	162,878	8.8
2	15	1,182	$1,700	$1,855	$3,555	18,199	161,224	8.7
3	30	1,174	$1,707	$1,835	$3,542	18,277	159,456	8.7
4	45	1,164	$1,710	$1,811	$3,521	18,313	157,370	8.6
5	60	1,152	$1,708	$1,786	$3,493	18,286	155,190	8.5
6	75	1,152	$1,726	$1,778	$3,504	18,477	154,567	8.5
7	90	1,154	$1,744	$1,775	$3,518	18,669	154,247	8.6
8	105	1,155	$1,758	$1,771	$3,528	18,816	153,906	8.6
9	120	1,158	$1,770	$1,770	$3,540	18,954	153,841	8.6
10	135	1,163	$1,781	$1,776	$3,558	19,073	154,391	8.7
11	150	1,172	$1,796	$1,790	$3,586	19,230	155,602	8.8
12	165	1,178	$1,799	$1,803	$3,603	19,264	156,738	8.9
13	180	1,186	$1,801	$1,818	$3,619	19,283	158,030	9
14	-30	1,207	$1,712	$1,905	$3,617	18,326	165,594	9
15	-60	1,206	$1,714	$1,903	$3,616	18,347	165,383	9
16	-90	1,187	$1,699	$1,868	$3,567	18,192	162,322	8.8
17	-120	1,175	$1,716	$1,833	$3,549	18,376	159,325	8.7

3.3 The Impact of Shading and Landscaping on Energy Use/Cost

As shading is one of the important ways of reducing cooling loads, the effect of shading implementation on energy use has been examined to acquire the optimal shading depth. Figure 5 shows that utilizing external shading depth with value equal to 2/3 windows height achieved the maximum saving of the annual energy cost by 4.0%. Landscaping, i.e. trees, is another important factor that can impact the energy demand for the building. Trees can provide natural shading as well as barrier against wind speed. In this sense, trees were added, and the energy consumption were examined. It was observed that utilizing both shading and landscaping has reduced the energy consumption by 6.25% of the lifecycle cost.

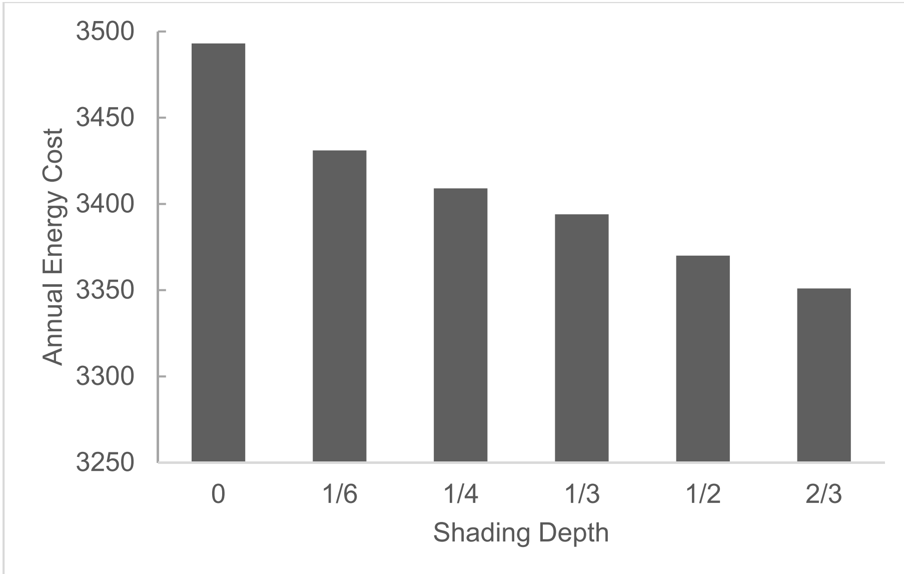

Figure 5: Shading impact on energy cost

3.4 The Impact of WWR on Energy Use/Cost

Windows are one of the weakest thermal points in buildings and play an important role in energy consumption. To evaluate the impact of windows size and attain the optimal WWR, many test scenarios were conducted. As shown in Table 2, WWR (15%) achieved the maximum saving of the annual energy use by 45.43%. In the light of this context, it is important to mention that designers should wisely select windows size as their influence on building energy consumption is undeniable.

Table 2: Impact of WWR on energy use/cost

Test no.	WWR	Energy Use Intensity (MJ / m² / year)	Total Annual Cost			Total Annual Energy		
			Electric	Fuel	Energy	Electric (kWh)	Fuel (MJ)	Carbon Emissions (Mg)
1	15%	1,061.7	$1,442	$1,704	$3,146	15,438	148,122	7.1
2	30%	1,222.0	$1,642	$1,970	$3,611	17,575	171,184	9.0
3	40%	1,335.3	$1,763	$2,166	$3,929	18,878	188,233	10.3
4	50 %	1,448.1	$1,880	$2,363	$4,243	20,131	205,352	11.6
5	65%	1,613.3	$2,045	$2,654	$4,699	21,894	230,710	13.5
6	80%	1,803.9	$2,254	$2,982	$5,237	24,137	259,205	15.7
7	95%	1,991.3	$2,460	$3,305	$5,765	26,335	287,248	17.9

3.5 The Impact of Window Types on Energy Use/Cost

Window properties, i.e. glaze type, is a key factor of controlling the light and heat transmission into the building. To asses the impact of window types on energy load, 10 types were tested. In this regard, windows U-value and SHGC have been examined to estimate their influence on the total energy consumption. Table 3 shows that window type 6 (triple glazing low-e) acquired the best energy saving, which approximately accounts for 19.8%.

3.6 The Impact of Wall Materials on Energy Use/Cost

To measure the impact of walls thermal resistance (R), energy use has been evaluated among various R values from 10 to 44. Figure 6 shows that walls with R (44) is expected to save 13.4% of the annual energy cost. Based on this result, improving wall insulation can damp the fluctuation between the indoor and outdoor temperature.

Table 3: Impact of windows' types on energy use/cost

Test no.	Type of Window	Property		Energy Use Intensity (MJ/m² /yr)	Total Annual Cost			Total Annual Energy		
		U	SHGC		Electric	Fuel	Energy	Electric (kWh)	Fuel (MJ)	Carbon Emissions (Mg)
1	Type 1	4.34	0.77	987.4	$1,374	$1,570	$2,945	14,715	136,470	6.3
2	Type 2	1.96	0.67	977.3	$1,350	$1,559	$2,909	14,458	135,463	6.1
3	Type 3	1.67	0.42	989.3	$1,389	$1,568	$2,957	14,868	136,279	6.3
4	Type 4	1.67	0.29	1,007.4	$1,330	$1,634	$2,964	14,245	141,988	6.4
5	Type 5	1.32	0.28	994.9	$1,324	$1,609	$2,933	14,176	139,842	6.2
6	Type 6	1.42	0.36	957.4	$1,349	$1,515	$2,864	14,447	131,685	6.1
7	Type 7	1.78	0.2	1,029.8	$1,330	$1,683	$3,014	14,243	146,299	6.6
8	Type 8	1.49	0.15	1,019.1	$1,324	$1,662	$2,987	14,181	144,469	6.5
9	Type 9	1.78	0.15	1,032.2	$1,330	$1,689	$3,019	14,238	146,775	6.6
10	Type 10	1.26	0.47	975.6	$1,331	$1,564	$2,894	14,246	135,898	6.1

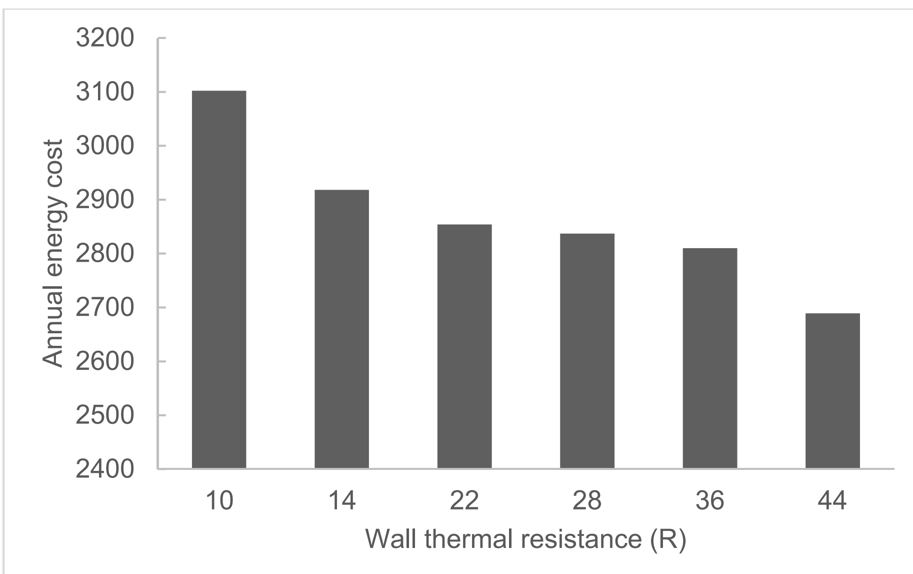

Figure 6: Impact of wall insulation on energy use

3.7 The Impact of Roof Materials on Energy Use/Cost

Roofs are another critical element of the building envelope as they are highly susceptible to solar radiation and other environmental changes. To assess the roof efficiency, energy use has been evaluated among various roof thermal resistance. As illustrated in Table 4, roof with super high insulation is expected to reduce total lifecycle cost by 30%.

3.8 Final Energy Performance

To further assess the building energy performance, Autodesk Insight A360 was utilized to combine all parameters into a single scenario. The integrated features of the final model have been examined and optimized to acquire better energy efficiency. It has been noticed that orientation at 90+ east north of south with WWR of 27% has reduced the energy use of the building. Figure 7 shows that the final mean energy use (192 kWh/m^2/year) of the building is less than ASHRAE's 90.1 recommendation. Figure 8 depicts a comparison results before and after implementing sustainable features. The results show a significant improvement in terms of peak monthly electricity consumption, peak monthly fuel consumption, net CO2 emission, and total lifecycle cost. Thus, it is economically feasible to implement the sustainability features towards efficient utilization of energy, as well as the carbon footprint.

Table 4: Impact of roof insulation on energy use/cost

Test no.	Thermal Resistance	Energy Use Intensity (MJ / m² / year)	Total Annual Cost			Total Annual Energy		
			Electric	Fuel	Energy	Electric (kWh)	Fuel (MJ)	Carbon Emissions (Mg)
1	Wood frame without insulation	1,208.9	$1,595	$1,961	$3,556	17,075	170,467	8.8
2	Wood frame with code compliant insulation (R 15)	878.8	$1,280	$1,372	$2,652	13,701	119,286	5.1
3	Wood frame roof with high insulation (R 30)	837.4	$1,251	$1,294	$2,545	13,393	112,447	4.6
4	Wood frame with Super high insulation (R 60)	815.9	$1,236	$1,253	$2,489	13,234	108,897	4.4

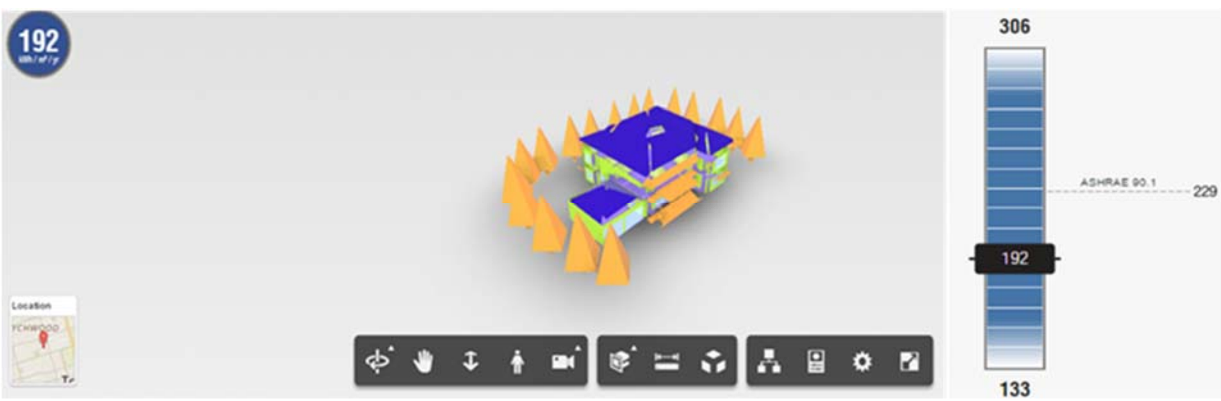

Figure 7: Building energy performance in Autodesk Insight A360

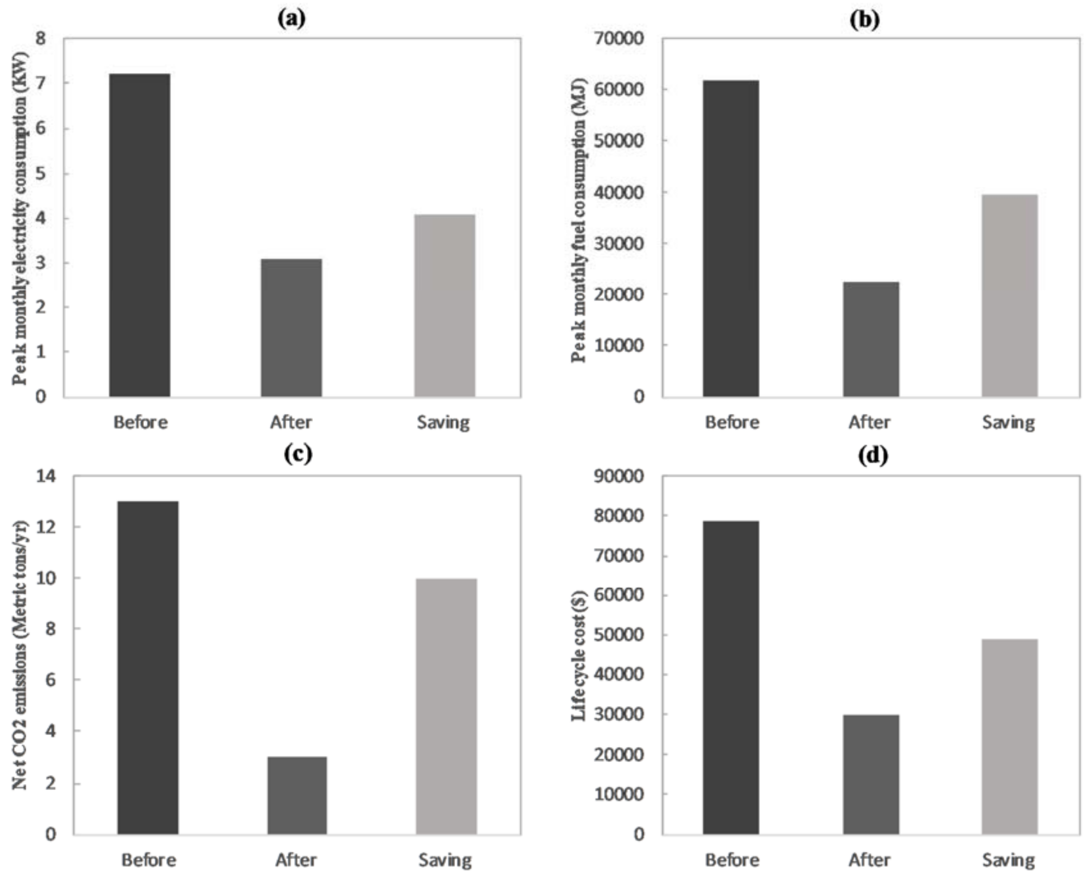

Figure 8: Performance before and after implementing sustainable features

4 SUMMARY AND CONCLUSIONS

This paper attempts to integrate sustainable passive features in the design of new buildings to enhance the energy performance and assess the impacts of the adopted sustainable features. BIM tools used to virtually simulate and analyze the impact of building form, orientation, shading, and building envelope on the energy consumption. The results revealed that building envelope has a remarkable impact on the energy saving, in which, WWR 15%, window type "triple glazing low-e", wall insulation R-value 44, and roof insulation R-value 60 have attained the best energy saving of 45.43%, 19.8%, 13.4%, and 30%, respectively among the study cases. In addition, building form yielded promising results by reducing energy consumption 38.2%. Likewise, shading has reduced the energy use by 6.25%. By combining the orientation +90° and WWR 27%, the energy performance of the building has shown further improvement. The total savings in the peak monthly electricity and fuel consumption, were 4.1 KW and 39,500 MJ respectively, while the saving in net CO_2 emission was 10 Metric tons/year and the total lifecycle cost reduction was $48,897. It is fair to conclude that adopting the sustainability concept towards efficient utilization of energy, has resulted in reduced energy consumption as well as the carbon footprint.

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