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INVESTIGATING THE IMPACTS OF PASSIVE DESIGN SOLUTIONS ON BUILDING ENERGY CONSUMPTION USING OPENSTUDIO: CASE STUDY OF A PRIMARY SCHOOL, HANOI, VIETNAM

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Abstract

It is crucial to investigate the factors influencing building energy expenditure to ensure sustainable buildings in the circumstance of a global energy crisis. The building energy simulation model is a crucial tool to support architects and engineers during different stages of building construction and operations to optimize the design solutions and operation schedules. The objective of this study is to analyze the unexplored combination of some passive design solutions including a one-story-primary school in Hanoi, Vietnam. The obtained results indicated that using sunshades, reducing the window-to-wall ratio (WWR), and improving the thermal insulation and glazing resistance to solar radiation of the building envelope would decrease the annual energy use intensity (EUI) of the building. More specifically, the building can reduce energy consumption from 2.87% to 5.10% by replacing double-glazing glass with low-E glass. In addition, decreasing the WWR by 30%, the annual EUI of the building reduced from 5.05% to 8.49%. Similarly, displacement of the red brick by aerated concrete brick to construct the external wall would reduce energy consumption from 0.45% to 1.36%. Furthermore, the presence of sunshades on the west side of the building would decrease annual EUI from 1.04% to 2.52%.

Keywords: building energy simulation; OpenStudio; passive design solutions; primary school; Hanoi.

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1. Introduction

Buildings consume large amounts of energy in the construction field worldwide. According to previous research, it is predicted that building energy use will increase by 32% by 2040 [1]. The operation and maintenance processes of buildings consume up to 40% of total energy worldwide [2]. Instructional buildings including educational and commercial buildings consume large amounts of energy due to high people density and various functions of interior spaces [3]. In Vietnam, the construction industry plays an important role in the economic structure and is related to many different industries and fields. According to reports from the Ministry of Construction (2023), the average annual growth rate of the construction industry is currently from about 7% to 9% [4, 5]. The urbanization rate was about 42% by the end of 2023, rapid urbanization has increased pressures related to energy demand in the construction field [5]. Therefore, the application of sustainable concepts in the design, construction, and building operation processes has become a central concern. The research directed to highly efficient energy-used buildings is very necessary because of its scientific and significantly practical contributions to promote economical and efficient energy consumption in the building sector.

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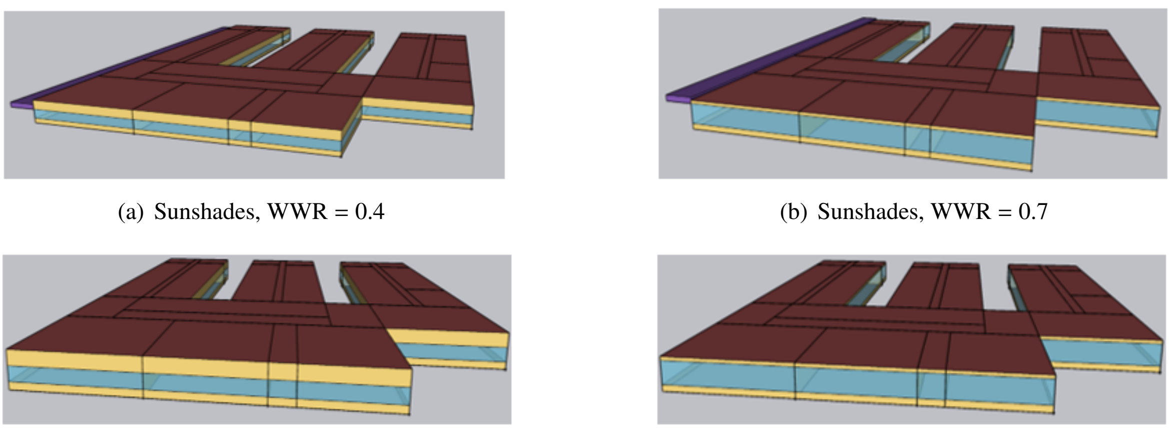
BEM is a practical and supportive approach for the optimization of energy-efficient buildings during the whole lifecycle of building such as the design stage, operation stage, and even retrofitting stage to ensure improvement of energy performance and carbon emission reduction. BEM tools such as OpenStudio [6], BuilderDesign [7], TRNSYS [8], DeST [9], and Modelica [10, 11] are widely used to simulate overall building performance by considering various building characteristics and specifications including schedules, internal loads, building geometry, construction materials, etc. Generally, most of the BEM models are physical model groups, using energy balance, conductivity, heat transfer, and mass balance to describe the building complex system.

There has been plenty of research around the world applied building energy models (BEM) to simulate the energy and environmental performance, to optimize the building design solution including building envelope, building geometry, building operation pattern, and HVAC system control [2, 3, 7, 12–14]. However, there have been a few studies related to BEM application in Vietnam. Nguyen Anh Tuan and Tran Anh Tuan [15] applied OpenStudio to investigate the impact of climate change on the building envelope of commercial and office buildings in Vietnam. Ngo et al. [16] applied building information modeling (BIM) technology and cloud-based energy analysis tools to model the energy behavior of an office building. However, according to our best knowledge, there hasn't been any study investigating the impact of building envelope materials, building façade, and air conditioning systems in an educational building in Vietnam. In this study, a building energy model of a primary school has been developed using OpenStudio to examine the effect of building envelope construction materials, sunshade solutions on energy consumption.

2. Methodology

2.1. Building description

Our study area is Hanoi, Vietnam. The weather in Hanoi was described in the previous studies [17, 18]. The geometric representation of the primary school building is given in Fig. 1. The height of the building is 4 m. The building type is a primary school. The primary school floor plan was presented in [19]. The space types in the school floor plan consist of the classroom, gymnasium, kitchen, cafeteria, office, mechanical, corridor, lobby, and restroom. To investigate the impact of passive design solutions including materials of external windows and walls, sunshades, and the window-to-wall ratio (WWR), we developed 16 different cases of building energy models. In all cases, the



(a) Sunshades, WWR = 0.4

(b) Sunshades, WWR = 0.7

(c) No sunshades, WWR = 0.4

(d) No sunshades, WWR = 0.7

Figure 1. The geometric representation of the primary school building

building is assumed to have installed a package terminal heat pump (PTHP) air conditioner. The design day data for Hanoi downloaded from http://energyplus.net/weather was used to size the HVAC system automatically to regulate the internal environmental conditions. The detailed combination of the type of external window glass, type of external wall brick, WWR, and sunshade for each case was presented in Table 1. In each case, we changed only one parameter and kept the remaining factors constant. The information on materials constructed in the building envelope of 16 different investigated cases was taken according to Tri et al. [16] and was listed in Table 2.

Table 1. The information of material constructed the building envelope of 16 different investigated cases

Case	The glass type of external windows		WWR		Brick type of external walls		Sunshades	
	Double glazing glass	Low E glass	0.7	0.4	Red brick	Aerated concrete brick	Yes	No
1	x		x		x			x
2		x	x		x			x
3	x			x	x			x
4		x		x	x			x
5	x		x		x		x	
6		x	x		x		x	
7	x			x	x		x	
8		x		x	x		x	
9	x		x			x		x
10		x	x			x		x
11	x			x		x		x
12		x		x		x		x
13	x		x			x	x	
14		x	x			x	x	
15	x			x		x	x	
16		x		x		x	x	

Table 2. The detailed information of building envelope constructions

External wall	Red brick external wall: 0.015 m of plaster; 0.22 m of red brick; 0.015 m of plaster	Aerated concrete brick external wall: 0.015 m of plaster; 0.22 m of aerated concrete brick; 0.015 m of plaster
Flat Roof	0.015 of ceramic tiles; 0.01 m of plaster; 0.03 m polystirol layer; 0.05 m of cement mortar layer; 0.002 m; 0.002 m of Polymer cement mortar for waterproofing; 0.12 m of Reinforced concrete; 0.015 m of internal cement mortar; 0.009 m of gypsum board.	
Ground floor	0.1 m concrete poured directly onto the ground + 0.05 m Cement mortar + 0.02 m ordinary brick mixed with light mortar	
Glass	Double glazing glass includes clear glass mm + Air 3 mm + clear glass 6 mm (U = 3.63 $W/m^2.K$; SHGC = 0.7; VLT = 0.78)	Low-E glass (bronze 6 mm+ Argon 13 mm+ Clear glass 6 mm) with U = 2.5 $W/m^2.K$; SHGC = 0.5; VLT = 0.47.
Sunshade roof	Add sunshades extending 1 m for west-facing windows	

2.2. Building energy simulation approach

This research uses EnergyPlus software to perform energy simulations of a school for different cases based on the solution of the building's constructions and air conditioning system. OpenStudio was released by the National Renewable Energy Laboratory (NREL) in 2010 to optimize the time and expense of developing new Building Energy Model applications. Since then, OpenStudio has been a widely used and trusted tool for many research relating to building energy simulation. The workflow to simulate the energy of a building using OpenStudio is described in Fig. 2. In this study, we used Sketchup software to create detailed building geometry in three dimensions, create and assign individual spaces, assign building stories and exterior spaces, and assign the thermal zones. Besides Sketchup software, the floor plan editor integrated within the OpenStudio application can be used to develop a two-dimensional floor plan for each building story. Then, OpenStudio was applied to specify the weather, materials, and construction assemblies of a building, define schedules applied to building loads, and define building loads. In the next step, we specified HVAC systems and assigned zone equipment in the OpenStudio Application. Finally, we run the simulation for each case, review the results, and analyze, and compare the obtained results.

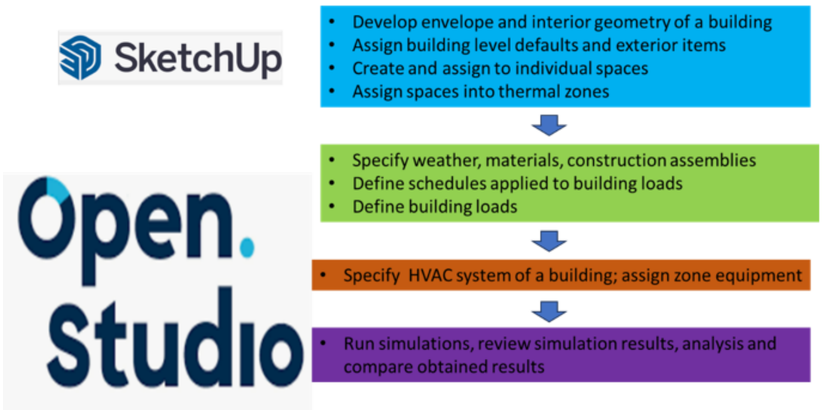


Figure 2. Flow work to perform building energy simulation of a building using OpenStudio

The input data of the OpenStudio model includes building geometry and spaces, constructional information, climate data, energy uses and thermal load, HVAC data, and schedules. The building geometry and spaces of the primary school were generated using Sketchup software. The building envelope isolates the interior from the outdoor environment and creates comfortable, productive, and safe environments for the occupants. To maintain occupant comfort, the interior space of a building is installed with heating, ventilation, and air conditioning (HVAC) systems. This HVAC system consumes a large amount of electricity. The smaller the thermal resistance of the building construction materials, the larger energy transfers through the building envelope leading to more electricity consumption used for the HVAC system. Therefore, the specification of building envelope constructions plays an important role in maximizing occupant comfort and minimizing the energy consumption of a building. In this study, we conducted the building energy simulation for 16 different cases with different constructions of external walls and window glazing. We also investigated the role of sunshade roofs and WWR (Table 1). The weather has a significant impact on the energy transfer through a building. However, weather condition changes from year to year. Therefore, the OpenStudio model used Typical Meteorological Year (TMY) to present the annual average weather and the range of weather extremes of a given location. TMY for Hanoi was downloaded from EnergyPlus Weather (EPW). TMY is an important input of the OpenStudio model that expresses the weather conditions surrounding the building.

Besides the weather conditions, the construction of the building envelope, and the activities inside the interior spaces (occupancy and energy end uses) also influents the energy consumption of a building. Energy end uses including lighting, electric, and gas equipment not only consume energy directly but also release heat to the space that impacts the capacity of the HVAC system. The interaction of occupancy and energy end uses is an important thermal load component that drives the whole building energy simulation. The occupancy and energy end uses of the primary school are chosen according to TCVN 5687:2024/BXD, QCVN 09:2017/BXD, and ASHRAE 90.1-2010 standard [20], and listed in Table 3.

The thermal load within the spaces depends on occupant, lighting, and equipment schedules. We assume that the primary is closed at the weekend. The school day starts at 7:30 am and finishes at 16:30 pm. Lunch break is between 11:30 am to 13:30 pm. During the lunch break, the students and staff have lunch at the cafeteria. The air conditioning systems operate from 7:30 am to 16:30 pm with a cooling set point temperature of 25 °C and a heating set point temperature of 21 °C. The total heat of occupant releasing to the space including sensible and latent heat is assumed to be 132 W/person. The lighting power density of the building system is listed in Table 3.

Table 3. Occupancy, electric equipment power density, and lighting power density of the building

Space	Occupancy density	Electric equipment power density	Lighting power density
Cafeteria	1 m^2/person	18.51 W/m^2	6.99 W/m^2
Classroom	2 m^2/person	10.98 W/m^2	12 W/m^2
Corridor	1.01 m^2/person	2.91 W/m^2	7.10 W/m^2
Gymnasium	3.33 m^2/person	3.66 W/m^2	12.92 W/m^2
Kitchen	6.67 m^2/person	3.66 W/m^2	10.66 W/m^2
Mechanical	10 m^2/person	3.66 W/m^2	10.23 W/m^2
Office	8 m^2/person	7.86 W/m^2	11 W/m^2
Restroom	10 m^2/person	2.91 W/m^2	10.55 W/m^2

3. Results and discussions

3.1. Energy consumption of the primary school building and impact of glass types and WWR on building energy consumption

Among the components of the building envelope, transparent windows generated a large heat loss proportion of the building (20% - 40%) [21]. Thermal heat imparting to the indoor spaces through external transparent windows includes conduction, convection, and radiation. The solar heat gain through windows depends on the solar radiation magnitude of the local area. Thus, transparent windows would be a significant driver of energy consumption for the HVAC system of the building in Hanoi because Hanoi has an average annual total solar radiation of about 3.96 kWh/m^2 [22]. According to Nguyen et al., [15] it is necessary to combine different passive design solutions such as using sunshades, enhancing the glazing facade's resistance to solar radiation, and thermal insulation to optimize the energy efficiency of the building. Therefore, in this study, we examine the influence of different combinations of glass types and WWR of external windows. The double-glazing glass and low E glass were taken into account with two WWR (0.7 and 0.4). We also consider the impact of the brick type constructed on the external wall on the building's energy consumption. Two types of bricks are investigated including red brick and aerated concrete brick. In addition, the ability to reduce the energy consumption of the sunshade roof on the west of the building is also accessed. We combined the different types of glass, brick, WWR, and sunshade roofs into 16 cases as represented in Table 1. The energy consumption of the primary school building in Hanoi ranged from 156.08 to 178.81 kWh/m^2. Our obtained results were in the range of institutional buildings in Singapore (141.4 kWh/m^2 to 288.4 kWh/m^2) [3].

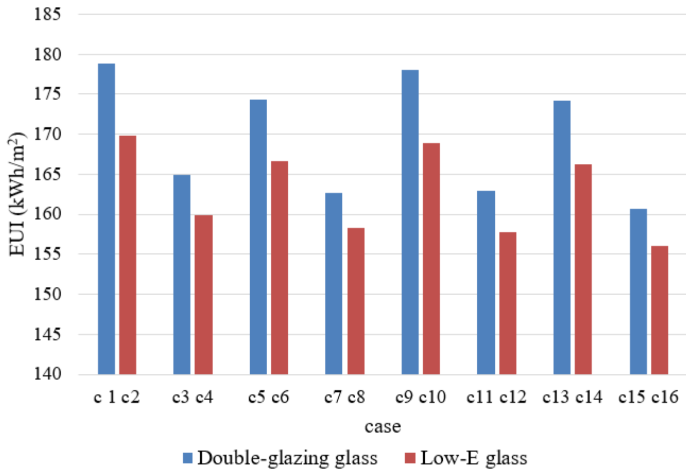


Figure 3. Impacts of glass type of external window on energy consumption of a building

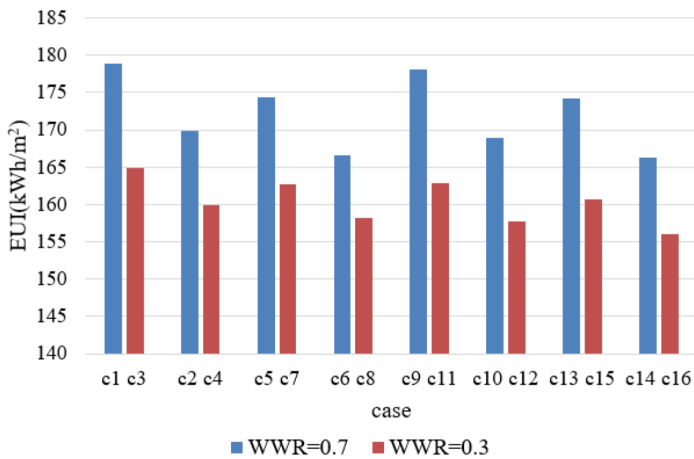


Figure 4. Impacts of WWR of the external window on energy consumption of a building

As shown in Fig. 3, the building with external windows constructed by double glazing glass consumes more energy than the one with low E glass. The building can reduce energy consumption from 2.87% to 5.10% by replacing double-glazing glass with low-E glass. This can be explained by double-glazing glass having a higher U-value and higher solar heat gain coefficient (SHGC) value than the low E glass. The U value or thermal transmittance is defined as the speed of heat transfer through a unit of time and the surface of the construction element. While the U value presents the non-solar heat, SHGC expressed the amount of solar radiation passing through the window, and quantifying the solar heat gain. In hot humid climate areas such as Hanoi, Vietnam, the higher the U values, the higher the SHGC values, the larger the heat load in the internal areas of the building, and the more building energy consumption. Fig. 4 shows that the higher the WWR, the more energy the building used. The building may save from 5.05% to 8.49% by decreasing the WWR from 0.7 to 0.4. In other words, a reduction of 30% of WWR would lead to the reduction of building energy use by 5.05% to

8.49%. Our obtained results were higher than in the previous study [1]. Furthermore, both displaced the double glazing glass by low E glass and reduced the WWR by 30%, while the remaining other parameters are unchanged, leading to a 9.22% to 11.39% reduction of annual EUI. The result can be attributed to the higher U-value of the glass compared to the wall constructions. Furthermore, the heat gains from solar radiation through external window glass also lead to higher energy used. The results obtained in this study are smaller than the results obtained in Amaral et al., [23] which reported an increase of 20%-30% in energy efficiency of the building by replacing the window materials.

3.2. Impact of brick types of external wall on building energy consumption

The external wall is one of the important components of the building envelope that separates the interior from the outdoor environment. The building envelope not only protects the interior from weather phenomena, but also creates a safe, comfortable, and productive environment for people through the operation of HVAC. The energy consumption of the HVAC system strongly depends on the thermal performance of the building envelope. Therefore, the thermal conductivity characteristics of the external wall also impose an influence on the energy consumption of a building. We examine the impact of brick types, one important material of external wall construction on the building energy consumption. Fig. 5 expressed the slightly higher energy consumption in the case of an external wall constructed with red brick compared to that of aerated concrete bricks. Displacement of the red brick with aerated concrete brick to construct the external wall would reduce energy consumption from 0.45% to 1.36%. This could be attributed to the smaller thermal conductivity coefficient of aerated concrete bricks (0.153 W/m.K) compared to red bricks (0.81 W/m.K). The smaller the thermal conductivity coefficient of the brick, the higher the thermal resistance of the external wall construction, the less thermal transmittance through the external wall, and the less energy consumed by HVAC systems.

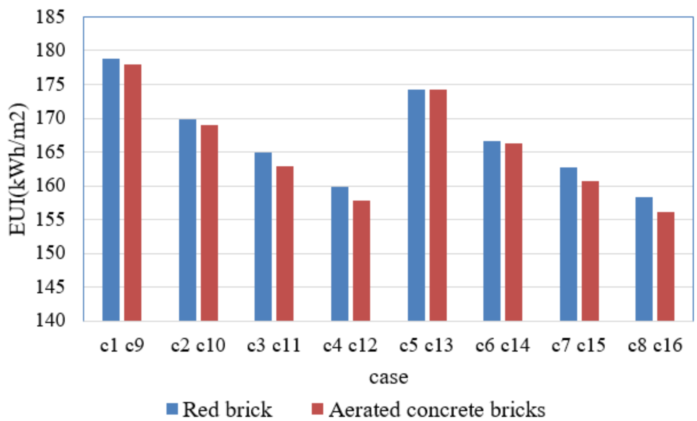


Figure 5. Impacts of brick type of external wall on energy consumption of a building

3.3. Impact of sunshades on building energy consumption

As discussed in section 3.1, types and WWR of external windows play important roles in the energy efficiency of the building. Especially, the windows on the western façade of the buildings high incident radiation on window planes. The common sunshade systems include consoles, shutters, and vertical-horizontal bas, which can be fixed or adjusted manually or mechanically [24]. This study investigated the energy consumption effect when a horizontal sunshade on the west side of the building was installed. The sunshade provides a supplement dimension to the flat surface of the building would improve energy efficiency. The presence of sunshades reduces direct sunlight entering through windows and doorways, which results in better temperature regulation of the building, and lower energy consumption for the air conditioning system. As shown in Fig. 6, the building installed sunshades on the west expressed lower EUI values than the one with no sunshades. Adding sunshades on the west side of the building would decrease energy consumption from 1.04% to 2.52%. Kazaz and Yetim [24] also reported a total annual energy saving of 8.4% by using fixed sunshades. Thus, the horizontal sunshades would decrease energy consumption, and energy costs by reducing the glare, and heat gain from the sun, allowing the natural light illumination for the interior building. Moreover, by integrating all the better passive design solutions, the building could save up to 12.71% of the energy consumption.

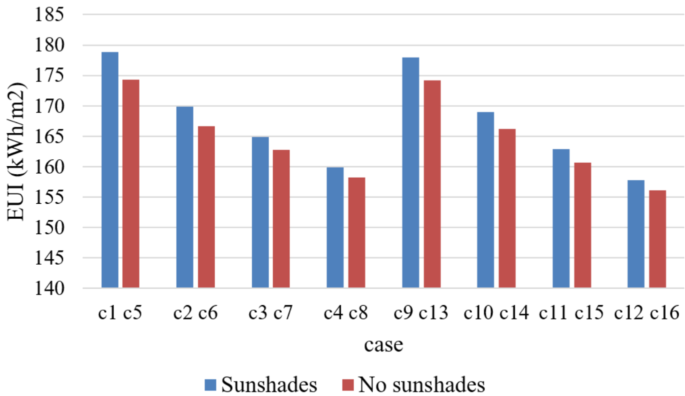


Figure 6. Impacts of sunshades on energy consumption of a building

4. Conclusions

Although there has been an abundant number of recent research on the application of BEM for building energy optimizations worldwide, there is little research related to this field in Vietnam. Especially, there is an evident gap in exploring multiple passive design solutions to improve building energy use. Thus, in this research, we conducted various extensive energy building simulations, the integration of multiple passive design solutions to effectively minimize the energy consumption of a primary school building. We investigated the impacts of several passive design factors including the utilization of sunshades, reduction of WWR, and improving the thermal insulation and glazing resistance to solar radiation of the building envelope According to our obtained results, the building can reduce energy consumption by replacing double glazing glass by low E glass (2.87% to 5.10%), decreasing the WWR (5.05% to 8.49%), displacing the red brick by aerated concrete brick to construct the external wall (0.45% to 1.36%), and adding the sunshades on the west side of the building (1.04% to 2.52%). The results of this study would provide scientific-based evidence in making decisions on future sustainable building designs.

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