

## RESEARCH PAPER

### Sustainable Architecture Environment

# Analysis of Optimum Window-to-Wall Ratio in Horizontally Expanded and Vertically Expanded Windows in Tehran, Iran

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#### Abstract

Good daylighting design in buildings not only provides a comfortable, luminous environment, but it also helps save energy and create a comfortable and healthy environment for the occupants of the building. The importance of receiving daylight in educational buildings is due to the time synchronization of operating hours of the school, and daylight plenitude in the sky. Daylight improves environmental quality and saves energy by minimizing artificial lighting requirements and, thus, reducing the cooling load. Furthermore, window design is a primary sustainable approach to achieving environmental goals and contributes to comfort and satisfaction. The present study analyzes the variations of annual thermal energy demand and useful daylight illuminance to determine the optimal Window-to-Wall Ratio (WWR) of a simulated primary school classroom in Tehran in two directions of the south and the north. Twelve different window sizes in two types of horizontally expanded windows (the height of the window remains constant, the width is varied) and vertically expanded windows (the width of the window remains constant, the height is varied) were compared from the two perspectives of Useful Daylight Illuminance (UDI) and thermal and electrical energy using the Honeybee plugin of Grasshopper. The results of this research demonstrate that vertically expanded windows are more energy-efficient in classrooms while they give almost the same UDI as horizontally expanded windows in both south and north facades. Overall, WWR in the range of 25% to 35% in the south facade displayed the best performance in daylight and thermal loads.

**Keywords:** Classroom, Daylight, Honeybee, Window-to-wall ratio (WWR).

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## 1. INTRODUCTION

The demand for energy is rising extremely fast, while at the same time, energy supplies are facing a severe shortage with almost the same fast pace [1]. Since it has profound implications for humanity's social-economic and political sphere, energy consumption has increasingly become a topic of serious consideration in various aspects of human activities [2]. Buildings are one of the main concerns in energy consumption. European studies on energy consumption show that buildings account for 40% of energy use and 30% of CO<sub>2</sub> emission [3]. Daylighting design and building design should always be integrated into a creative process aimed at generating appropriate architectural and technical solutions while reducing building energy consumption [4]. Passive solar energy utilization in building design can contribute to the reduction of dwelling energy consumption and enhancement of indoor thermal comfort [5]. The first step in passive solar design is to optimize the orientation of a

building, which strongly depends on its passive solar heat gain elements, their orientation, and their position in a building [6]. The next step is to design windows and other openings which is a principal factor in the energy-based architecture. The conditions for indoor environmental parameters have far-reaching implications for people's health, general well-being, and performance [7]. The fact that people prefer to live and work in buildings that have windows is generally accepted and widely documented [8]. In addition to their psychological effect, windows play an important role in reducing energy consumption in buildings. Also, the opening design on building facades has a great influence on daylighting, solar heat gain, and natural ventilation, which are closely linked to lighting, air conditioning, and energy consumption [9-10]. Since windows are one of the weakest parts of a building envelope thermally [11], choosing window features is a key step in the design of a building [12]. Optimizing window characteristics in the early stages of design has no impact on the initial cost of the construction but will reduce the costs generated during the operation of the building [13]. Building facade design with an appropriate window to wall ratio can contribute significantly to minimizing energy loss. In educational spaces, good

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daylight has come to be closely associated with improvement in student performance and the promotion of better health [14]. Providing an adequate amount of evenly distributed daylight and glare prevention are important challenges in classroom design [15]. It should be noted that taking into consideration thermal and daylight performances together is highly important. They are, in turn, affected by numerous correlative factors such as glazing size and characteristics, shading properties and its control system, and room aspect ratio and its orientation [16]. In this research, a parametric window of a classroom is optimized based on daylight availability and thermal and electrical performance to find the best optimum WWR. Achieving Work Plane Illuminance (WPI) in the range of 500-2000 Lux, which is a suitable illuminance range of educational environments [17-18] was the goal of this research.

## 2. LITERATURE REVIEW

The contemporary global energy crisis has led to the quest for ways to conserve energy in buildings [19]. To this end, certain guidelines such as window structure should be taken into consideration. Previous research on the optimum WWR has consistently taken only one aspect of window function, such as thermal consumption, into consideration; for example, a parametric study evaluated the window-to-floor ratio of three window types (single, double, and triple glazing) considering annual thermal comfort assessment of a space in the city of Coimbra, Portugal [20]. Another study investigated the impact of orientation, size, and thermal properties of the glass material of windows on heating and cooling energy demand of a typical residential building in Palestine using the IES and Ecotect software [21]. In these studies, daylight is ignored and only cooling and heating energies are considered. In a study, a questionnaire was used to find out the relationship between students' perception and satisfaction with daylighting in a school regarding south- and north- oriented classrooms [22]. Another research that investigated daylight without thermal factors showed that the most appropriate options for offices in Tehran were WWR %30, %35, and %40 [13]. Some studies evaluated thermal and lighting energy consumption simultaneously; for example, Mohammad Kari et al. optimized window width-to-height ratio (WHR) and sunshade dimensions of the south wall of an educational building in Tehran and proposed horizontal windows with higher sill level [23]. Zomorodian et al. found that by increasing the WWR to 35%, 40%, and 50% and by installing a roof monitor, the daylight credits of BREEAM and LEED could be achieved respectively [15].

Some studies found that the smaller WWR, the lower

energy loss would be. One paper, for instance, examined the influence of the glazed part of the envelope of a building and determined that the smallest window-to-wall ratio and north orientation were preferred [24]. Yang et al. found that the total energy consumption of a residential building (heating and cooling energy demand) increased when the window-to-wall ratio was also increased, especially in the east and the west facade [25]. Rashid et al. conducted a study to obtain a desirable window size (WWR) for a commercial building in Lahore and the results showed that there was a gradual decrease in heat gain by decreasing the size of the window and vice versa, especially in the south facade [26].

Ghiai et al. investigated the relationship between the window to wall ratio (WWR) and energy consumption in high-rise office buildings that were constantly subjected to climatic conditions in Tehran and the results indicated that the WWR affected energy consumption differently on the different sides of the base-case model [27]. Other research examined the impact of glazing to floor ratio of energy, daylighting, and thermal comfort in nearly zero energy houses, using EnergyPlus and Daysim and emphasized that windows in south-oriented rooms had to be carefully designed in order to prevent overheating [28]. Another research employed the four factors of shading device, window to wall ratio, window height, and glazing in designing energy-efficient windows in classrooms to reduce energy consumption for supplemented lighting and mechanical ventilation, using Ecotect simulations and concluded that projected clerestory was the most energy-efficient window design [29].

In this study, Honeybee, which is a validated software for thermal and daylight calculation, is used to evaluate all energy consumption (heating, cooling, and electricity), in addition to daylight factor (UDI), and to find the best WWR for the north and the south facade of a primary school in Tehran.

## 3. RESEARCH METHODOLOGY

In light of recent advances in energy software, computer simulation has gained greater popularity in the methodology in related research methodology [30]. The method applied in this study is simulated using Honeybee 0.0.57 and Ladybug 0.0.60, which are plugins for grasshopper 0.9.0076 on the Rhinoceros 5 software. This software has the ability to analyze daylight and thermal load in the simulated space. The grasshopper environment allows the researcher to test and compare the parametric geometries. The simulated model was originally developed in Tehran, Iran, with the latitude of 35.41° and longitude of 51.19° and with hot and dry climate, climate zone 4B. The research methodology is presented in Fig. 1.

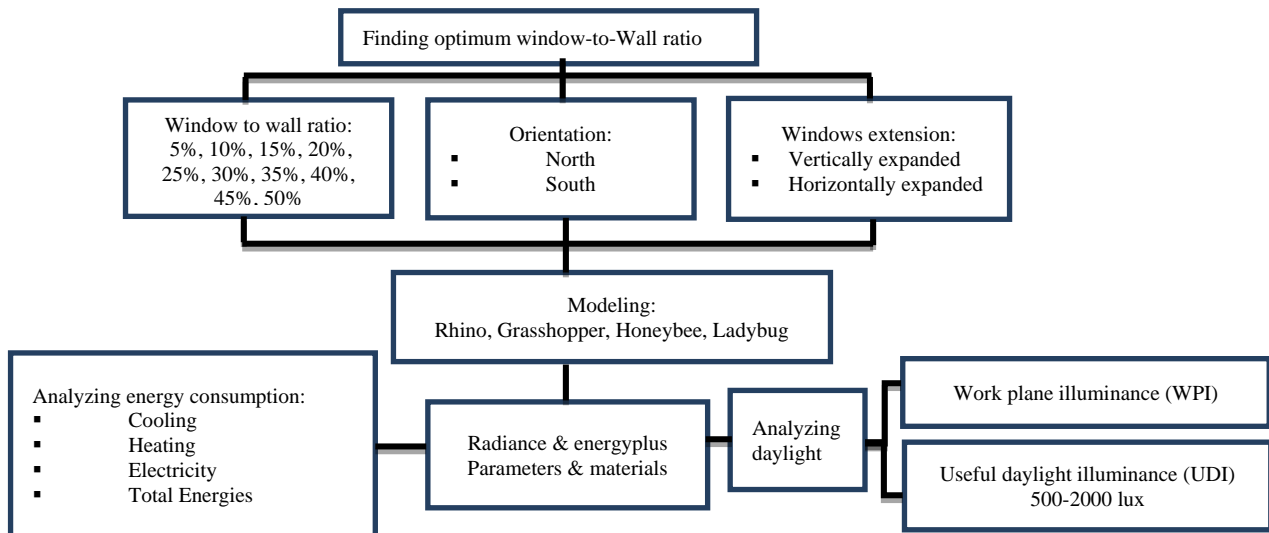


Fig. 1 Research Methodology

### 4. MODEL DESCRIPTION

A sample room was simulated as a classroom with the external dimension of 8 m in width, 6 m in depth, and 3.5 m in height, located on the first floor of a hypothetical primary school building. The window area limit is described in Fig. 2. The maximum lintel level is 1.90 m and the maximum window width is 7.40 m. The window sill is assumed at the height of 1.3 m to prevent students from getting distracted from conducting their tasks.

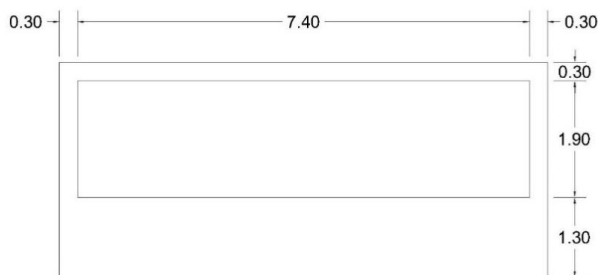






















Fig. 2 The window area limit

To find the optimum WWR, two types of ranges were applied to the window size, i.e. the vertically expanded and horizontally expanded model first introduced by Mahdavi et al. [31]. 20 different window models with square shapes were tested and the design tool was tested with both north-oriented and south - oriented views. Each window extends 5% - the minimum amount of the window size - in dimensions compared to the previous one, until 50% - the maximum amount of window size in this research based on structural and architectural considerations. In sum, the model windows of the research include 10 vertically expanded and 10 horizontally expanded windows, as shown in Table 1.

The grid size is 50 centimeters and the distance to the floor is 50 centimeters as well [32], which is the appropriate distance for primary school desks.

The windows were assumed with no shading device, as well as with 0.85% visible transmittance glazing type and reflectance index of 0.05%. Interior walls have the diffuse reflectance of 0.05%, the roughness of 0, and the specularity of 0.05 %.

Table 1 10 vertically expanded windows and 10 horizontally expanded windows modeled in this research

WWR	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
Vertically expanded	 7.4×0.19	 7.4×0.38	 7.4×0.56	 7.4×0.75	 7.4×0.94	 7.4×1.13	 7.4×1.32	 7.4×1.51	 7.4×1.7	 7.4×1.89
Horizontally expanded	 0.73×1.9	 1.48×1.9	 2.21×1.9	 2.95×1.9	 3.68×1.9	 4.42×1.9	 5.16×1.9	 5.9×1.9	 6.63×1.9	 7.37×1.9

For both vertically expanded and horizontally expanded windows, the sill height was considered 1.3 m from the floor, which is the standard value for primary school classrooms. As can be seen from Table 1, the first group (vertically expanded) was started by a window with a width of 7.4 m and the height of 0.19 m. The percentage of WWR increases each 5% until a window 7.4 m wide

and 1.9 m high is obtained. For the second group, it starts with a window 1.9 m high and 0.73 wide and ends with the same as the last window in the first group, i.e. 1.9 m high and 7.4 m wide.

Assigned materials are listed in Table 2 and radiance parameters are presented in Table 3.

**Table 2** Assigned materials selected for this research

	EP (Energy Plus) Material	Radiance Material
Main wall	Ashrae 90.1-2010 ExtWall Mass climate zone 4 U value: 0.55	RGB reflectance 0.5 Roughness 0 Specularity 0.05
Adjacent walls	Interior Wall, U value: 2.58	RGB reflectance 0.5 Roughness 0 Specularity 0.05
Ceiling	Ashrae 90.1-2010 ExtRoof IEAD climate zone 2-8 U value: 0.28	RGB reflectance 0.8 Roughness 0 Specularity 0.05
Floor	Ashrae 90.1-2010 ExtFloor Climatezone 2-7 U value: 0.15	RGB reflectance 0.2 Roughness 0 Specularity 0.05
Window	Ashrae 90.1-2010 ExtWindow Nonmetal climate zone 4 U value: 2.27	RGB transmittance 0.0654 Reflective index 1.54

**Table 3** Radiance Parameters selected for this research

ab: Number of ambient bounces	6
ad: Number of ambient divisions	1500
as: Ambient super-samples	128
ar: Ambient resolution	16
aa: Ambient accuracy	.025

## 5. EVALUATION METHOD

Work Plane Illuminance (WPI), as an indicator of daylight, is used to check the quality of daylight in spaces. Different places, due to the different nature of activities in different places, need different amounts of WPI [33]. In the work plane, the student table is considered as 50 centimeters high. The WPI then should be 500 Lux to be able to offer enough potential for reading and writing [18]. To obtain the optimum WWR, useful daylight illuminance 500-2000 under the climate-based sky was applied. The increase of WWR entails the increase of the area with more than 2000 Lux which leads to the glare and an undesired amount of light. The decrease of WWR entails the increase of the area with less than 500 Lux, which is insufficient for the classroom without using electricity. Daylight illuminances in the range of 100-500 Lux are considered effective in conjunction with artificial lighting. Daylight illuminances in the range of 500-2000 Lux are often perceived as either desirable or, at least, tolerable [17]. Therefore, achieving more illuminance in the range of 500-2000 Lux on the work plane was the goal of this research. The amount of illuminance received on the work plane is calculated based on the percentage. For each window sample, the spatial percentage of the students' table plane which achieves illuminance in the

range of 500 to 2000 Lux during the whole year, is calculated and compared with each other. The standard occupant air temperature of 24°C during cooling and 19°C during heating for EnergyPlus zone thresholds are considered. The analysis period was from September 23<sup>rd</sup> to June 21<sup>st</sup>, and the school hour was from 8 a.m. to 2 p.m.

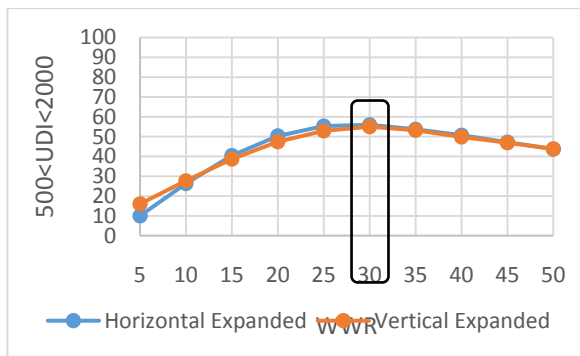
## 6. RESULTS AND DISCUSSION

The results are analyzed in two parts, i.e. finding the optimum WWR according to UDI and thermal energy consumption.

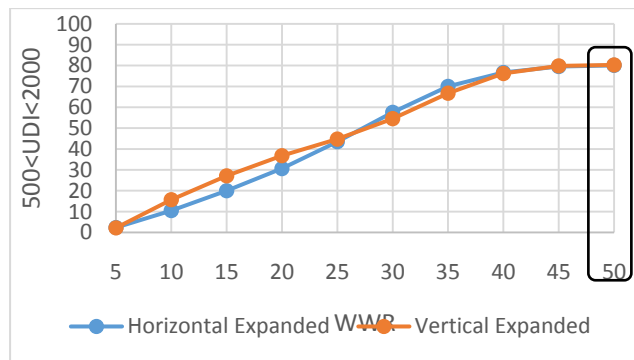
### 6.1. Optimum WWR according to UDI

In this section, the percentage of work plane illuminance in the range of 500-2000 Lux for each WWR is determined. As shown in Fig. 2, there is not much difference in UDI 500-2000 in horizontally expanded and vertically expanded windows.

In the south facade Fig. 3a, the optimum window to wall ratio is 30% in horizontally and vertically expanded windows, and in the north facade Fig. 3b, the optimum window to wall ratio is 50% in horizontally and vertically expanded windows.



a: UDI in the south facade



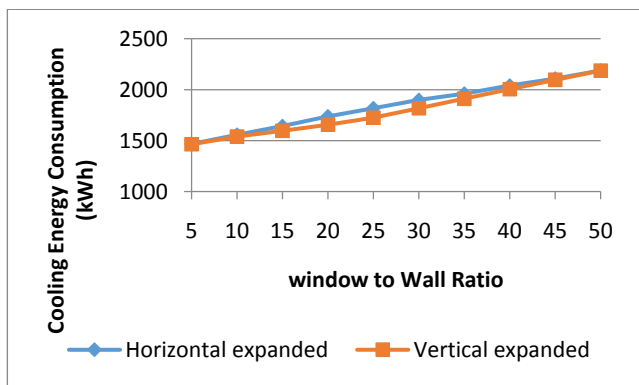
b: UDI in the south facade

Fig. 3 UDI in the south and north facade

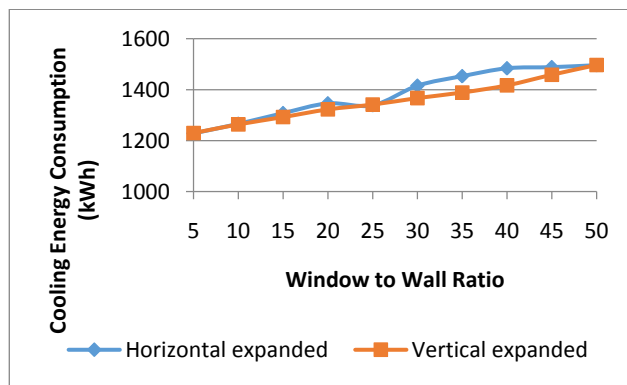
6.2. Optimum WWR according to energy consumption

- **Cooling energy consumption:** The higher the WWR, the more cooling energy use. Vertically expanded

windows use less energy than horizontally expanded windows in both south and north facades Fig. 4.



a: Cooling energy consumption in the south facade

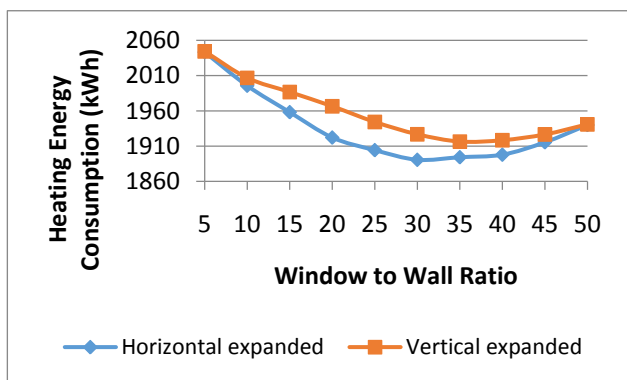


b: Cooling energy consumption in the north facade

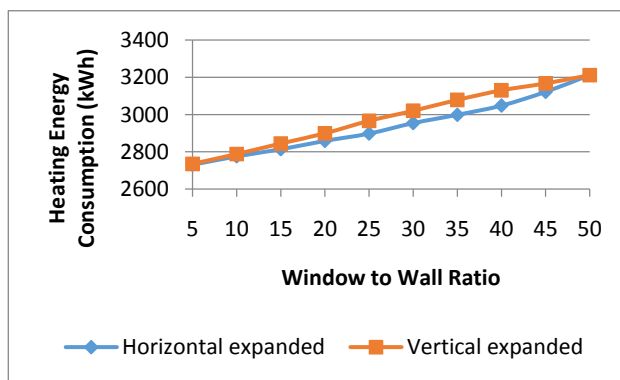
Fig. 4 Cooling energy consumption in the south and north façade

- **Heating energy consumption:** In the south facade, heating energy consumption has a reverse correlation with WWR up to 30% in horizontally expanded windows and 35% in vertically expanded windows, and it increases after that Fig. 5a. In the north facade,

heating energy consumption has a direct correlation with WWR. The higher the WWR, the more energy consumption. Horizontally expanded windows save more energy compared to vertically expanded windows Fig. 5b.



a: Heating energy consumption in the south facade

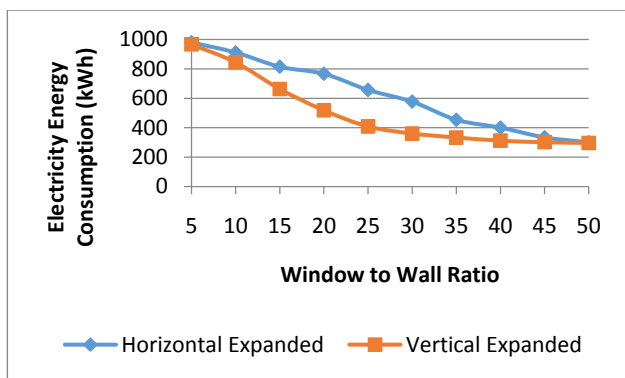


b: Heating energy consumption in the north facade

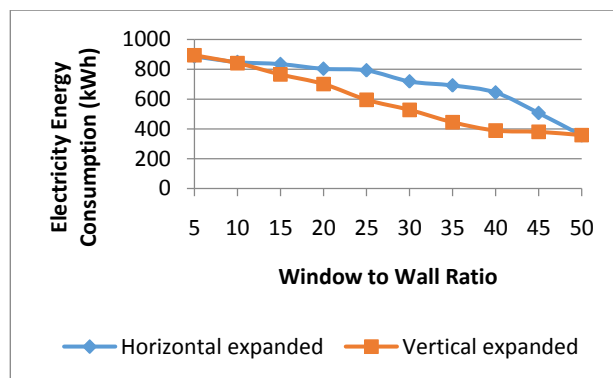
Fig. 5 Heating energy consumption in the south and north façade

- **Electrical energy consumption:** As the window size increases, electricity consumption in both north and south facades decreases, however, vertically expanded

windows use less electricity compared to horizontally expanded windows Fig. 6.



a: Electrical energy consumption in the south facade

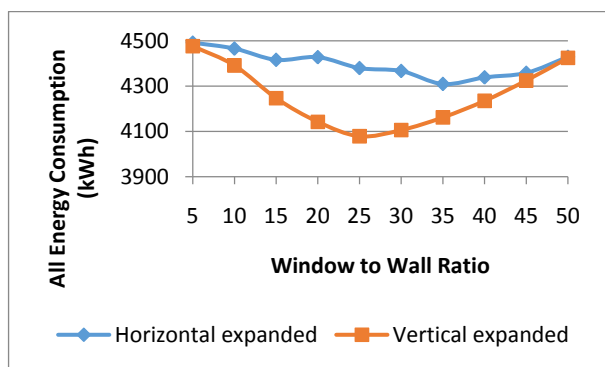


b: Electrical energy consumption in the north facade

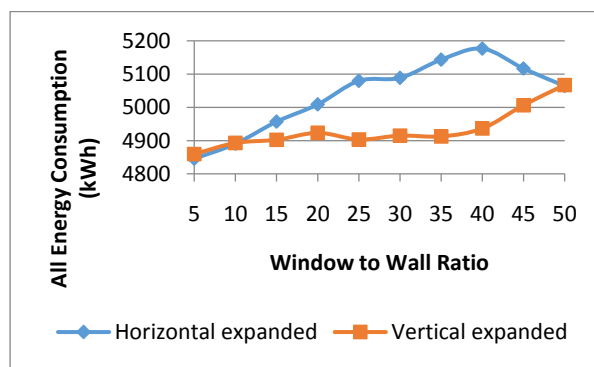
Fig. 6 Electrical energy consumption in the south and north facades

- **Overall energy consumption:** Fig. 7 shows that in general, vertically expanded windows, in all ratios of window to wall, use less energy than horizontally expanded windows. Also, the optimum WWR in the south facade based on energy consumption is 25% in

vertically expanded windows and 35% in horizontally expanded windows. In the north facade, the smaller the window size, the less energy it consumes, hence 5% optimum WWR in the north facade.



a: Overall energy consumption in the south facade



b: Overall energy consumption in the north facade

Fig. 7 Overall energy consumption in the south and north facades

## 7. CONCLUSION

The aim of this paper is to determine the approximate window to wall ratio for south and north orientated classroom using the simulation method. Window area or the window-to-wall ratio is an important variable that affects the energy performance in a building. The window area affects heating, cooling, and lighting in buildings and is also linked with the natural environment regarding access to daylight, ventilation, and the view. The results of this study showed that horizontal windows (vertically expanded windows) are more energy-efficient compared to vertical windows (horizontally expanded windows). In addition, the best WWR, according to thermal load energy, in the south facade is 25% in vertically expanded windows and 35% in horizontally expanded windows. In the north facade, the smaller the window size, the lower the energy consumption will be. In terms of daylight, there was not much difference in horizontally and vertically expanded windows, but in the south facade, the best WWR that gets more Useful Daylight Illuminance (UDI) is 30% and in the north facade, it is 50%. As a result, a WWR in the range of 25% to 35% in the south facade has the best performance

regarding daylight and thermal loads. In the north facade, the daylight and thermal loads have opposite results (the higher the WWR, the higher UDI and the lower energy-saving), therefore, it is difficult to offer a distinct percentage for this direction. In case which appropriate daylight comfort desired, windows with higher insulation should be used so that thermal energy consumption will be reduced.

## CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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