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OPTIMIZATION OF WINDOW-WALL-RATIO USING BIM-BASED ENERGY SIMULATION

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Abstract. In this research, sensitivity analysis is applied to investigate the impact from U-values of walls, U-value of windows, and the window-to-wall ratio. The purpose is to find the co-relationship between those parameters with the building energy performance, including embedded energy in materials and operational energy during the lifecycle. Building Information Modeling (BIM) is used as a platform to obtain the material quantities and carry on energy simulation. A case study is applied for a manufactory plant in Suzhou, China. By applying both local sensitivity analysis and global sensitivity analysis, it is found that thermal properties of walls have insignificant impact on Operational Energy to Embodied Energy (OE-EE) relationship of Window-Wall-Ratio (WWR) whereas changing thermal properties of windows affects the OE-EE relationship behaviour of WWR. Lowering U-value of windows brings positive impact to the OE-EE relationship of WWR, and vice versa. Therefore, suggestions are made as reducing/increasing U-value of windows while increasing/decreasing the WWR of building.

Keywords. Building Informaion Modeling; Window-Wall-Ratio; energy simulation.

1. Introduction

According to the European Union report, 40% of the total energy was consumed in the building sector. Over 80% of energy was consumed during building's operational stage. In addition, energy embodied in construction materials is also huge, e.g., producing cement is an energy-intensive process. Therefore, a proper building design help reduce building's environmental impact during its lifecycle. Architectural daylighting design is at the heart of sustainable building design. Daylighting, which is the use of natural light in a building, plays a significant role in reducing the amount of artificial lighting that is needed to light the interior of a building. When properly designed and effectively integrated with the electric lighting system, daylighting can offer significant energy savings by offsetting a portion of the electric lighting load. Larger window areas are preferred to allow more natural light into the building. However, larger value of window-wall-ratio (WWR) may cause more energy consumption to compensate heat loss through the building envelope during operational stage. Therefore, finding an optimal WWR to meet both natural lighting requirements and energy saving is essential. In this study, main design parameters that affect the building performance are selected, which include the U-value of walls, U-value of windows, and window-wall ratio, etc. Building Information Modelling (BIM) is used as a platform to enable energy simulation, material quantity take-off, and data integration. Simulation of energy consumption is run for different scenarios in terms of energy consumption during operation stage. Energy embodied in typical construction materials are calculated for each scenario and combined with the building energy consumption results from the energy simulation. Sensitivity analysis (SA) is applied to find the relationship between changing the parameter values and the energy performance of the building and impact of the WWR on building performance is identified.

2. Methodology

First of all, the base model of a building was created by BIM and the properties of building were defined in the model. Next, the energy baselines were calculated upon the base model, include operational energy (OE) and embodied energy (EE). BIM provides a quick access of materiel quantity so as to calculate the EE. The energy analysis was run iteratively by varying one or more design parameters while all other parameters were set to be constant. In this research, the output results of interest is the energy used in the building during its lifetime operational stage, i.e. operational energy (OE), assuming the lifetime of building is 50 years. With respect to each design parameter changes, the information of energy used in building were obtained from the simulation output result and the EE of building envelope was calculated based on the quantity and energy coefficient of material. Lastly, the correlation degree between OE and EE for each envelope element respect to the design parameter was measured and compared to identify the most influential design parameter which is the one that the output results have highest degree of variation with respect to its change. A sensitivity indicator was chosen to represent the sensitivity results, which provide the importance of design parameter to EE and OE of buildings.

Table 1. Typical Range and Recommended Maximum Value.

Design parameters		**Typical range**	**GB50189-2015 recommended maximum value**
U-value (W/m^2 K)	Wall	0.37 – 1.95	0.5
	Window	1.70 – 6.00	3.5
	Roof	0.18 – 3.00	0.8
WWR		0.10 – 1.00	-

To perform SA, the design parameters were varied in the model from baseline value within certain range and interval to create different scenarios, while other design parameters were fixed to its base model value. Table 1 tabulates the typical range and recommended maximum value by GB50189-2015 for the design parameters (Dowd & Mourshed 2015; Harwell 2016; Hussain 2015; Ioannou & Itard 2015). According to literature, the U-value of walls and roof are affected by thermal mass and insulation whereas for windows, the glazing type and number of layer are the impact factors to consider. The typical WWR is range from 0.10 - 1.00, as shown in table 1. It is defined as the ratio of window area (Awd) to wall area (Aw). The target WWR can be achieved by changing the size and number of windows. In this research, the latter was used as the approach to vary WWR. Depending on glazing type and the number of glazing layer, the U-value of windows was modified by varying the thickness of glass plane, which is the traditional variable of windows (Lam & Hui 1996). According to literature, for glazing with two or more layers, the ratio of air space between glass plane and thickness of glass was generally to be 2:1. Therefore, the air space was assumed to be twofold of the glass thickness. In this research, double layered window is considered. A sensitivity indicator was selected to evaluate the sensitivity of design parameters on OE. Different methods for sensitivity analysis, both local and global, are available, such as sensitivity coefficient (SC), standardized regression coefficient (SRC), etc. In this research, SC and SRC were selected as local and global sensitivity indicator respectively to measure the sensitivity of each design parameter on OE of building and its energy-efficiency. Due to space limit, only the result of SC is presented in this paper.

3. Case Study

The case study is done based on a 3-storey industrial plant under construction in Suzhou.

3.1. BASE MODEL DESCRIPTION

The 3D model of a manufacturing building was created by using Autodesk Revit. While the building energy analysis was performed by Energy Analysis (EA) option in Revit. It is an add-in tool for Autodesk Revit that links the design feature of the model to analysis feature of Green Building Studio (GBS). The energy simulation performed in GBS uses DOE2 simulation program to run building model simulation with the purpose of producing sustainable and energy efficiency design in the earlier stage (Mohammad & Shea 2013). This program has been used widely to perform energy modelling and its accuracy and consistency have been validated. However, DOE2 has limitation in dealing with complicated model that consists of large number of data required to handle and analyze (Ochoa et al. 2012). Therefore, to guarantee robustness and consistency, the model was simplified to consider only first floor of case study building for energy simulation. The details of case study building are given in table 2. Figure 1 shows the simplified first-storey model that was used for energy simulation in the research.

Table 2. Description of simplified case study building.

	Description
Floor area	1916 m^2
Height	6 m
Wall area	1128 m^2
Window area	202.46 m^2
Roof area	2402 m^2
WWR	0.22
External walls	Autoclave aerated concrete
Roof	Lightweight concrete
Windows	Double clear glazing filled with air

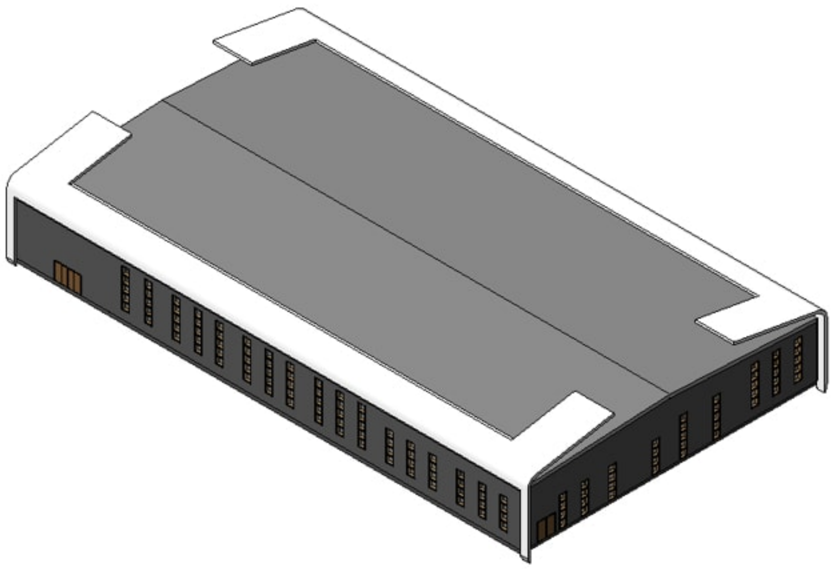

Figure 1. Simplified base model.

The design parameters of interest were varied by increasing and decreasing from base model value within certain range and interval as shown in table 3. As the target U-value of element is achieved by varying its thickness, the corresponding thickness of elements respect to the design parameters of model is calculated.

Table 3. Four design parameters.

Design parameters		Base model value[1]	Range	Interval
U-value (W/m² K)	Wall	0.50	0.35 – 0.65	0.05
	Window	3.00	2.10 – 3.90	0.30
WWR		0.22	0.00 – 0.34	0.04

As shown in figure 2, it was found that the U-value of walls and windows have strong positive linear relationship with the OE of building. These findings are in agreed with the study of Ioannou & Itard (2015) and Yu et al. (2013), which the higher the U-value of building envelope elements, the more energy is required to maintain the operation of building (Scheer 2013; Yu et al. 2013). Results show that the U-value of wall has the higher gradient slope value respect to OE of building. Therefore, to reduce building energy consumption, lowering the U-value of wall to improve the thermal properties of building envelope can be taken as a priority.

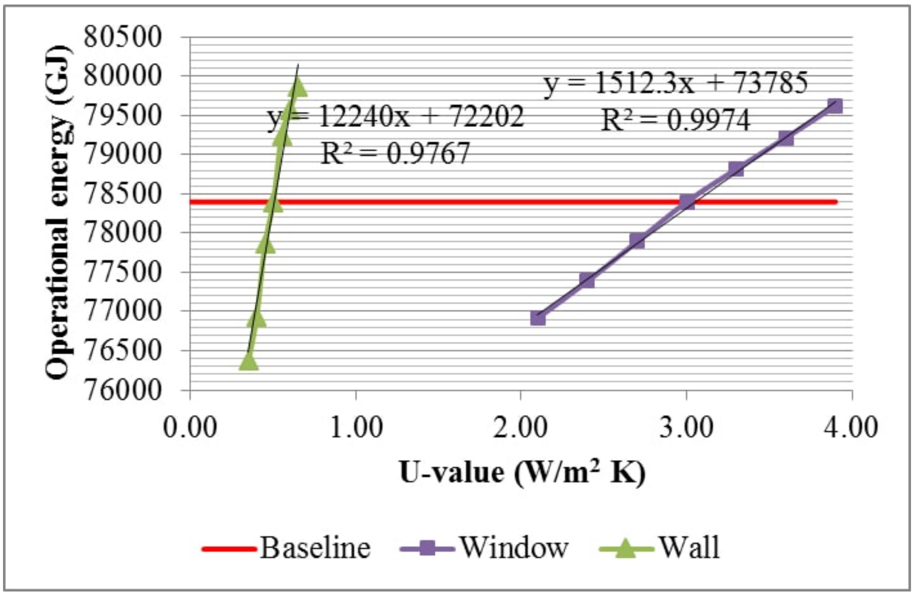

Figure 2. The impact of U-values of wall and window on OE of building.

Figure 3 shows the impact of increasing WWR on OE. It is a U-shaped curve with optimum lying at WWR of 14%. The variation of OE with WWR changes is attributed to the change in the area of windows and walls affects the thermal loads of buildings, such as solar heat gain, heat conduction across envelope element and internal heat gain, and subsequently impact the heating and cooling required by HVAC to maintain thermal comfort within buildings.

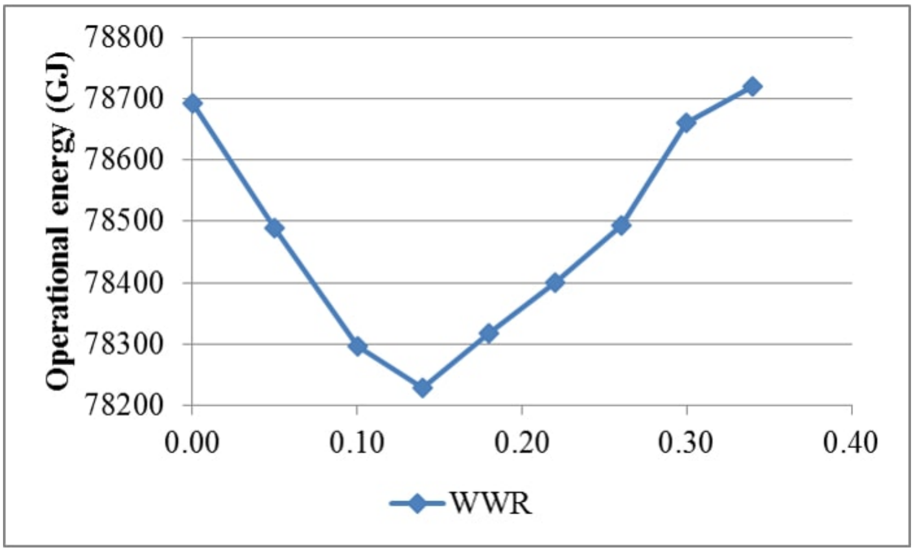

Figure 3. The impact of WWR on OE of building.

However, it was observed that the OE-EE relationship of WWR in LSA is neither linear nor monotonic when U-value of walls and windows were kept to its base value, i.e. the OE of building is inconsistent when EE of building envelope varied with WWR, contrasting with other design parameters. This is due to the thermal load of building changes inconsistently when WWR is varying. Besides, wall and window materials have distinct amount of EE, therefore the variation of WWR, which alters the area of wall and window in building envelope, would change the EE of building envelope as well. This brings out the need for GSA in order to explore more thoroughly the relationship between WWR and EE of building envelope, subsequently the impact on OE of building with considering the interactions among design parameters and offer more reliable energy saving practices.

In GSA analysis, the sensitivity of WWR on OE of building together when changing U-value of walls and windows simultaneously was investigated in 62 scenarios. As shown in figure 4, variation of OE with WWR in respect to change in U-value of walls or U-value of windows from its base value, while other parameters were kept constant. It was observed that with the increase of WWR, keeping U-value of windows to base value and changing U-value of walls from base value merely influences the amount of OE which the higher U-value, more OE is required (Line 1 and Line 5 in figure 4). This is due to change in heat conduction across walls associated with the variation of U-value and these practices would not change the relationship behaviour between OE and WWR as in figure 3, i.e. OE of building remains inconsistent with the variation of WWR. On the other hand, changing U-value of windows from base value affects trend behaviour of relationship between OE and WWR. For the scenarios of lowering U-value of windows and keeping U-value of walls to base value, instead of having inconsistent relationship between WWR and OE, the OE of building is decreased with increasing WWR (Line 4 in figure 4). In contrast, the OE in the scenario with higher U-value of windows is in opposite trend: it is increased with increasing WWR (Line 2 in figure 4). In summary, the findings from EE based LSA and GSA of OE with respect to the variation of WWR, U-value of windows and U-value of walls are summarized in table 4 as follows:

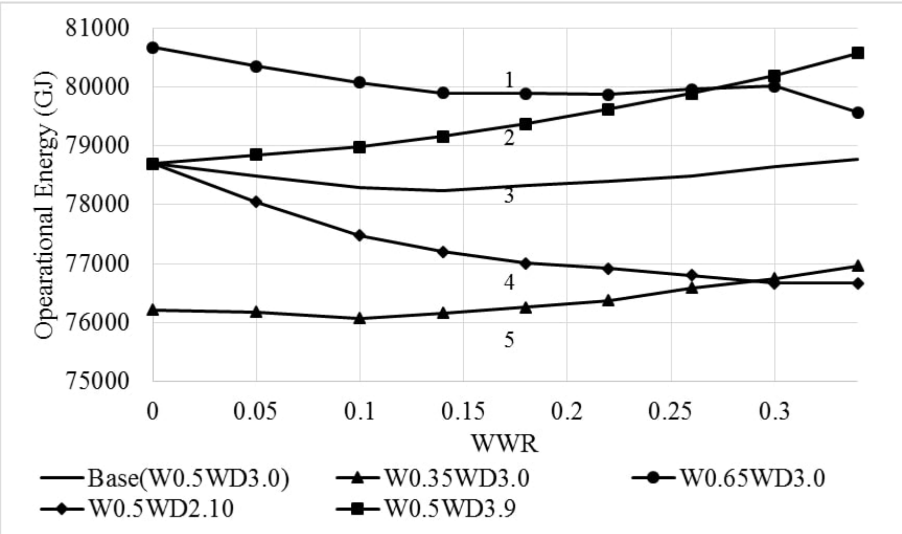

Figure 4. The variation of OE with WWR with respect to change in U-value of walls or U-value of windows.

Table 4. Summary of Findings.

No.	Findings
1	OE of building is more sensitive to the variation of EE due to U-value of windows changes and less sensitive to the variation of EE due to U-value of walls changes.
2	Thermal properties of walls have insignificant impact on OE-EE relationship of WWR whereas changing thermal properties of windows affects the OE-EE relationship behaviour of WWR.
3	Lowering U-value of windows brings positive impact to the OE-EE relationship of WWR.
4	Increasing U-value of windows brings negative impact to the OE-EE relationship of WWR.

Based on these findings, it was concluded that targeting on thermal properties of windows when varying WWR brings noticeable impact to both EE of building envelope and OE of building. Therefore, the suggestions for designer in selecting efficient building envelope designs are tabulated in table 5 as follows:

Table 5. Summary of Suggestions.

No.	Suggestions
1	Minimize U-value of windows and maximize U-value of walls during design stage
2	Minimize U-value of windows when consider to increase the WWR of building.
3	Maximize U-value of windows when consider to decrease the WWR of building.

4. Conclusions

Both LSA and GSA methods were used in this research to quantify the impact of input variation on output results. In LSA, the considered design parameters are U-value of walls, U-value of windows, and WWR. Sensitivity coefficient was selected as sensitivity indicator for LSA. Based on the proposed methodology, it was found that the OE-EE relationship of windows has steeper gradient slope. Therefore, among the element envelopes considered in this research, OE of building is most sensitive to the variation of EE due to U-value of windows changes. Therefore, targeting on thermal properties of windows during optimization process would bring the most benefit in term of LCE saving.

GSA focused on the OE-EE relationship of WWR by changing the U-value of walls and U-value of windows together. The findings from GSA are that the thermal properties of walls have insignificant impact on OE-EE relationship of WWR and lowering U-value of windows is the most influential energy-efficient practice that brings positive impact to the overall LCE of building. Therefore, when varying WWR during design stage, targeting on thermal properties of windows would bring noticeable impact to both EE of building envelope and OE of building and help to develop an energy-efficient design scheme that can reduce the overall LCE of building.

It was found that the scenario with the highest OE reduction or EE reduction is neither optimized nor energy-efficient from the perspective of LCE. Nevertheless, the top 5 energy-efficient scenarios are belonging to those with lower U-value of windows, which are in agreed with the findings from GSA, therefore this indicates that the findings from the proposed methodology in this research are reliable.

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