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An Evaluation of Window Parameters Effects on Daylight and Energy Saving in Residential Building in Saudi Arabia: An integrated optimisation and sensitivity analysis

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Abstract: Windows are a vital component of a building envelope that affect thermal and luminance levels; therefore, they are a leading variable in buildings' energy performance and occupants' well-being. Due to the often-conventional utilisation of windows and the absence of adequate design standards in Saudi Arabia, this study illustrates an approach to evaluate windows performance, providing a design criterion for designers and architects. The proposed approach evaluates a set of windows' parameters simultaneously, using genetic algorithm optimisation and sensitivity analysis. The aim is to investigate their interlocking relationship while highlighting the most influential parameters affecting energy saving, daylight, and thermal comfort. The study highlighted the importance of taking a holistic approach when optimising windows, considering both cooling and lighting energy. It was found that when windows' parameters are optimised, total energy consumption was reduced by 27%. Also, the results revealed that glazing has the most substantial impact on both cooling and lighting energy among window parameters.
Keywords: Windows parameters, thermal comfort, daylight, energy saving, genetic-algorithm, sensitivity analysis

1. Introduction

Maintaining a comfortable indoor environment is responsible for almost 70% of global energy consumption (Ganesh et al. 2021). It is argued that 50% of the energy loss in buildings is through windows (Grynning et al. 2013). Additionally, windows are found to be a leading variable in energy performance in hot regions (Alwetaishi 2022). With respect to research done in Saudi Arabia, it was found that few research papers have addressed the topic of window performance, with the existing studies focusing on the window-to-wall ratio (WWR) and shading devices or solely investigating glazing properties, as seen in the paper by Ghosh et al. (2021). The studies that investigated the WWR all indicated a need to keep the WWR between 20 and 30% for residential buildings (Alwetaishi and Taki 2020; Asfour 2020; Alwetaishi 2022). Alwetaishi suggested it should be 20% to balance energy consumption and daylight to reduce energy consumption for heating and cooling by 15% (2022). Research that investigates a wide range of window parameters simultaneously (glazing, size, orientation, shading, etc.) that is location-specific in Saudi Arabia, as seen in the work of Elghamry and Hassan (2020) and Alajmi et al. (2022), has yet to be identified.

In architectural research, there are various methods to conduct a study. A method which has been recently explored is genetic algorithm-based optimisation. This method has been facilitated in the studies by Alajmi et al. (2021) and Alajmi et al. (2022), which have been proven to be effective. This approach relies on the evolutionary principle of natural selection to find the best answer across several successive generations. According to Tuhus-Dubrow and Krarti (2010), compared to other traditional optimisation methods, this approach uses a population technique which evaluates all design variables simultaneously, rather than focusing on one potential solution at a time; this guarantees a more global optimisation strategy. Another approach frequently employed in building energy investigation is sensitivity analysis (SA) (Wei 2013). It is argued that since its benefits have been proven when applied in the early stages, it could be more effective and constructive when applied at a late stage of building design by concentrating on a few parameters of great value. A study by Mukkavaara and Shadram (2021) applied such an approach; the authors concluded that this strategy could help highlight whether the investigated design variations have a minimal or considerable impact on the objectives.

2. Methodology

The approach illustrates a strategy to evaluate window parameters simultaneously to investigate their interlocking relationship while highlighting the most influential parameters affecting energy saving while maintaining thermal comfort and adequate daylight levels. DesignBuilder® was used as a simulation tool. Figure 1 illustrates an infographic summarising the research methodology.

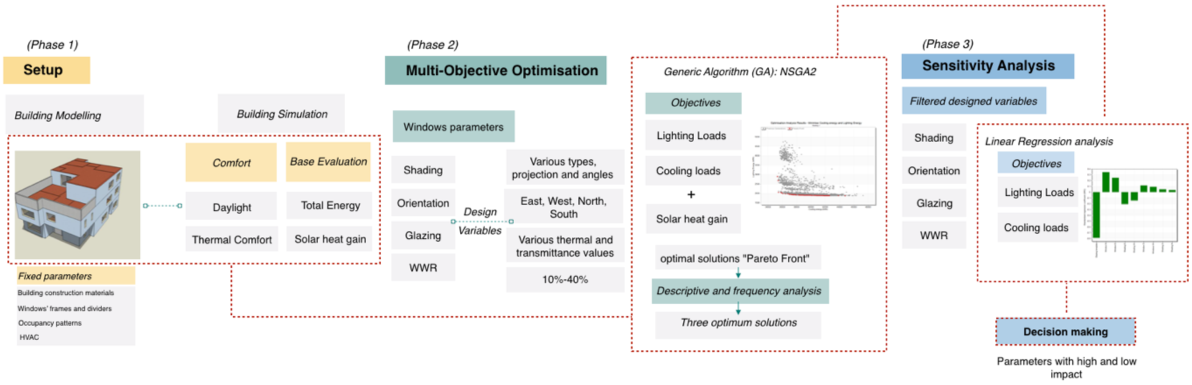

Figure 1. Research Methodology summary

2.1 Window Performance Indicators

Simulation runs are made to guarantee that the thermal comfort is not compromised and are set according to the predicted mean vote (PMV), which ranges from −+0.5 to −0.5, which comes following the ASHRAE Standard 55.

Artificial lighting energy consumption and daylight illuminance level have an inverse relationship, meaning the more daylight a space has, the less need there is to use artificial lighting to meet the target illuminance. Therefore, the light control option under the lighting tab in DesignBuilder® has been employed as an indicator of daylight availability. When employing this option, electric lights will be adjusted according to the amount of available natural daylight. The level of daylight has been evaluated following Mostadam's daylight requirements (a local buildings' ranking system), which required the measurements to be performed at noon on the summer solstice (21st or 22nd June), as summarised in Table 1.

Table 1. Daylight indicators

Period: 21 June, 12:00 pm (summer solstice)		
Minimum **200 lux** for 50% of net floor area		
Measurement Details	1 m square grid	0.75m above the floor
Lighting Control Sensor	Center of the rooms (approx. 2 m from the window)	

2.2 Brief about the case study

A building representing a typical single-family detached house that is referred to as a "villa" in Yanbu, Saudi Arabia was modelled. The total floor area is 226.9 m2, over two floors and an annexe. Plans can be seen in Figure 2. A set of static traits has been used to define the overall base model, such as construction materials, and internal gains, along with some windows components which are highlighted in Table 2. Base model window configurations were set as follows: 30% WWR, clear single glazing and no shading.

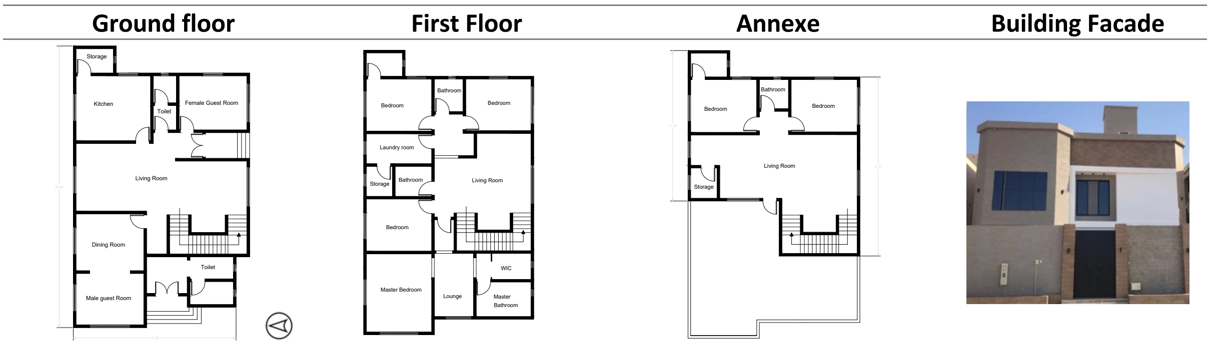

Figure 2. Case study

Table 2. Windows' Fixed Parameters

Window frames	Aluminium (with thermal break)			U-Value (W/m2-K): 5.014	
Window dividers					
Shading materials	Steel			Conductivity (W/m-K): 50	
Window height	1.5 m	**Sill height**	0.8 m	**Fixed WWR**	Toilets, bathrooms, storage _ 10%

2.3 Climate Conditions

Yanbu is located at 24.15 North and 38.067 East. Being situated in the northern hemisphere would imply that, the sun will always be in the south at its maximum altitude (solar noon). Yanbu is characterised by long summers with peak temperatures in June, July, and August.

2.4 Evaluated Parameters

To avoid unnecessary computing time, the parameters were carefully chosen by going through studies done in similar climates (see Table 3). A range of 14 different double and triple glazing, with a wide range of properties including clear, tinted, coloured and low-E and reflective glass and two-gap gas fills (air and argon) have been included. The segment of glazing properties was not discussed in terms of the aims of this paper.

Table 3. Matrix of design variables

Orientation	North, South, West, East			**WWR**		Min 10%, Max 40%, Sept: 5		
Shading	Louvres				Min 20°	Max 50°		increment: 10°
	Side-fins				0.3	0.5	0.75	1
	Three-sided fins				0.3	0.5	0.75	1
	Overhang				0.3	0.5	0.75	1
Glazing	**No.**	**U-value**	**LT**	**SHGC**	**No.**	**U-value**	**LT**	**SHGC**
	W1	2.66	0.78	0.70	**W8**	1.32	0.12	0.10
	W2	2.51	0.78	0.70	**W9**	1.75	0.73	0.68
	W3	1.76	0.74	0.56	**W10**	1.62	0.73	0.68
	W4	1.68	0.72	0.64	**W11**	0.98	0.66	0.47
	W5	1.76	0.44	0.38	**W12**	0.78	0.66	0.47
	W6	1.49	0.44	0.37	**W13**	1.21	0.32	0.25
	W7	1.61	0.12	0.11	**W14**	1.17	0.32	0.25

3. Results and Discussion

The preceding section discussed the base model performance results, to establish a baseline performance figure, and then investigate how the window parameters can improve the building's performance. Cooling loads are found to be the predominant annual energy consumption demand (73%) with an annual figure of 173749.45 kWh. Moreover, cooling loads were found to be at a maximum in the summer months of June, July, and August. Additionally, the simulation results illustrated that windows accounted for the largest share of heat gain, as seen in Figure 3. Since the investigation focuses on the hottest summer months (Jun, Jul, Aug), Table 4 illustrates energy consumption and solar heat gain solely in those months.

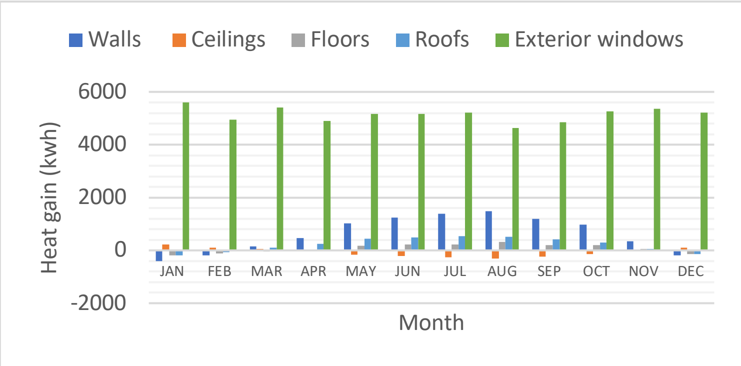

Figure 3. Base model component solar heat gain

Table 4. Base model performance (Jun, Jul, Aug)

Base model (kWh)		
Lighting	Cooling loads	External windows SHG
1835.79	49554.11	5007.38

3.1 Optimisation Results Analysis

The multi-objective genetic algorithm optimisation generated 4710 combinations, with 109 optimum solutions, as seen in Figure 4. The descriptive analysis results highlighted that the mean total energy consumption reduction for these Pareto Front solutions is 19% compared to the original case study's model. The lowest total energy consumption value is 37521.3 kWh, which accounts for a 27% reduction, while the highest total energy consumption is 46634.8 kWh, which accounts for a 9.2% reduction. The descriptive analysis showed that the standard deviation for lighting energy is very low compared to cooling, which means that switching between the selected design variables did not have a significant impact lighting energy load.

The selected three optimum combinations (minimum cooling, lighting, and total energy) are highlighted in Figure 4 and described in detail in table 5. First, the optimum solution demonstrated the lowest cooling load by around 29%, and the solar heat gain reduction by 70%. Nevertheless, the lighting energy increased by 57% compared to the base model. Daylight simulation was performed to assess the availability of daylight, it was found that the building suffers from poor of daylight levels (bellow 200 lux) in sever spaces in the building with the use of the windows parameters in this optimum solution. Second, the combination with the lowest lighting energy consumption shows that the lighting energy reduction was only 0.01%, and the total energy consumption was reduced by .09%, which is hardly a measurement of reduction. These results were expected, as the descriptive analysis highlighted that the standard deviation for lighting was very low; hence, there are low levels of variability in lighting energy values when changing design variables. Additionally, this solution caused the solar heat gain to double by 100%. Finally, looking into the optimum solution with the lowest total energy consumption, it was found that the total reduction of energy was around 27%, cooling loads reduced by 27% and lighting energy increased by only 11%. Moreover, solar heat gain decreased by 45.5%.

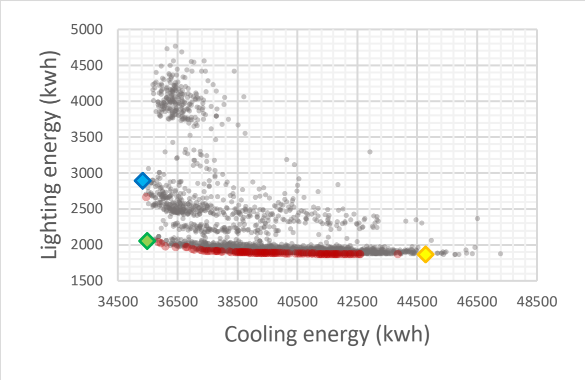

Figure 4. Pareto Front (Blue: Minimum cooling loads, Yellow: Minimum lighting loads, Green: Minimum total energy)

Table 5. Pareto Front Three Optimum Solutions

Optimum solution	Cooling	Lighting	Total
		kWh	
Min. Cooling	35318.6	2894.7	38213.3
Min. Lighting	44765.7	1869.1	46634.8
Min. Total	35471.4	2049.8	37521.3

3.2 Sensitivity Analysis Results

Frequency analysis has been conducted on the results of the multi-objective optimisation Pareto Front solutions, to highlight the most frequently used design variables across the optimum solutions, providing the sensitivity analysis with a reduced set of design variables. Table 6 highlights the refined design variables. Since each design variable will affect the cooling and lighting energy in its unique way, therefore the analysis was performed on these loads separately.

First, starting SA performed on cooling energy demand, the adjusted R-squared value was found to be high (0.9), indicating that the majority of the important sensitive input variables have been found. As seen in Figure 5, cooling energy was found to be most strongly influenced by the glazing template.

Second, looking into the SA executed with lighting energy set as the objective, the adjusted R-squared value was found to be "0.6", which is regarded as being somewhat low, which suggests that the current input variables may not be able to effectively explain the output's level of uncertainty. This observation is consistent with previous findings indicating that lighting energy has a low standard deviation. However, even though the current results might not be reliable to be used for identifying the most important input variables, the relationship of the individual variable to the output could still be relevant. As seen in Figure 5, glazing is found to be the parameter most influential on lighting energy.

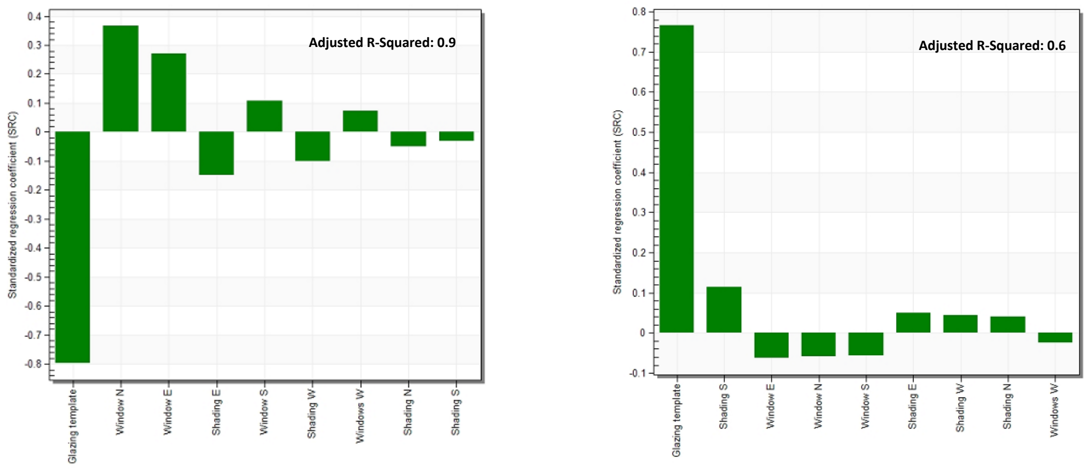

Figure 1. SRC Graph (Cooling and Lighting Energy, respectively)

Table 6. Flittered design variables Matrix

<table>
<tr><td colspan="2">WWR</td><td colspan="2">Min 10%</td><td colspan="2">Max 40%</td><td>Sept: 5</td></tr>
<tr><td rowspan="4">Shading</td><td>N</td><td colspan="2">Side-fins: .3–.5m</td><td colspan="2">Three-sided fins: .3–.5m</td><td>Overhang: .5m</td></tr>
<tr><td>W</td><td colspan="2">Louvres: 20°–30°–40°</td><td colspan="2">Three-sided fins: .3–1 m</td><td>Overhang: .75–1m</td></tr>
<tr><td>E</td><td>Louvres:40°-50°</td><td>Side-fins: .3m</td><td>Three-sided fins: .3m</td><td>Overhang: .5m</td><td>No Shading</td></tr>
<tr><td>S</td><td colspan="2">Side-fins: .3–.5m</td><td colspan="3">Three-sided fins: .3–.5-.75–1m</td></tr>
<tr><td colspan="2">Glazing</td><td>W1</td><td>W2</td><td>W3</td><td>W12</td><td>W14</td></tr>
</table>

4. Conclusion

This study's results demonstrated that windows have the solid potential to reduce building energy consumption when optimised, with the ability to reduce total energy consumption by up to 27% when window parameters are optimised. The findings also demonstrated that lighting energy has minimum fluctuation values when changing the window parameters variables. However, it is critical to consider it along with cooling energy, as the minimum total energy consumption while maintaining thermal comfort and adequate daylight levels was achieved by finding a soft spot between the two. Thereby, it is essential to take a holistic approach when attempting to optimise windows parameters. Finally, SA results revealed that glazing systems impact both cooling and lighting energy substantially.

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