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Assessment of Climate Change Impact in Tropical Buildings: Sensitivity Analysis of Light Shelf and Building Design Parameters for Daylighting and Thermal Balance

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ABSTRACT

Climate change may lead to more intense sunlight in tropical regions, potentially increasing the daylight available for buildings. While this can enhance natural lighting inside buildings, it may also exacerbate issues such as glare and overheating if not properly managed through shading devices and glazing treatments. Nevertheless, common strategies to mitigate heat gain and glare such as shades and blinds often obstruct natural light, necessitating increased reliance on artificial lighting. The conflicting interplay between daylighting and thermal performance can undermine building performance if not carefully considered. Existing research on the influence of key design parameters in tropical climates tends to focus predominantly on heat gain mitigation, neglecting other aspects. This study addresses these gaps by examining the holistic daylighting and thermal energy performance of buildings to develop optimised façade and resilient designs against climate change. The investigation encompasses an analysis of 11 design parameters of light shelves and building characteristics that are critical during the initial design stage. Global sensitivity analysis (GSA) is employed to identify the most influential design parameters affecting useful daylight illuminance, uniformity ratio, cooling energy, and solar gain energy. A case study involving double-story terrace houses in Malaysia is employed, with analyses conducted for the present and future climates of three Malaysian cities (Kuala Lumpur, Bayan Lepas, and Kota Bahru). The findings reveal that, across all three cities, glazing transmittance is the most influential parameter for daylighting performance, while room depth assumes primary significance for thermal performance. Although the relative ranking of parameters remains consistent between present and future climates, their magnitudes differ. In summary, this paper gives designers insights into the critical design parameters essential for achieving a balanced and resilient daylight-thermal design in tropical climates at the initial stages of the design process.

Keywords:
Sensitivity analysis; climate change; daylighting; energy efficiency; tropical region

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1. Introduction

Climate change has a pronounced impact on building design due to its influence on temperature and solar radiation which can affect buildings' comfort and energy performance [1]. In the context of tropical buildings where the temperature is relatively high throughout the year and the sunlight is intense, the implications of climate change are significant. Buildings in tropical climates are subjected to high temperatures and humidity levels for most of the year. Climate change can exacerbate these conditions, making it imperative for building designs to reduce heat gain without excessive reliance on energy-intensive air-conditioning systems [2,3]. As climate change increases average temperatures and potentially lengthens warm seasons, the demand for energy for cooling purposes might increase, leading to higher operational costs and contributing to the generation of greenhouse gases unless the design is optimized for energy efficiency [4].

Daylighting strategies may intensify the impact of climate change if careful design consideration is not considered to balance natural lighting with solar heat gain. The introduction of natural light into a space can reduce the need for artificial lighting during the day and positively influence a building's environmental performance. However, improper daylight design may lead to excessive solar heat gain, impacting the building's thermal performance negatively [5,6]. For instance, large windows allowing excess daylight might increase heating or cooling loads due to increased heat gains and losses [7]. Conversely, excessive control of daylight through shading could result in inadequate levels of natural light and higher energy consumption for artificial lighting. Hence, achieving a balanced approach between daylighting and thermal performance is crucial for comprehensive sustainable design [8].

One approach to solving the conflicting issues of daylight and thermal performance in tropical climates involves implementing a daylight system that can capture and evenly distribute daylight throughout the entire space. This system should also have the capability to manage excessive solar radiation by utilizing shading devices like overhangs, solar screens, blinds, louvres, etc. By integrating this system, it is possible to decrease potential heat gain and glare while redirecting a significant amount of natural light deeper into the space. Such an integrated solution offers a more even distribution of daylight while also reducing excessive solar heat gain from entering the interior [9]. This concept can be implemented using one of the most widely used daylight systems in modern buildings, known as light shelves. Light shelves are a simple way to achieve two purposes: reducing excessive heat and directing useful daylight deeper into space [10]. They consist of a horizontal or slanted surface that can be installed inside or outside a window above eye level, dividing the window into upper and lower parts. The upper part, called clerestory, reflects daylight towards the interior ceiling and back into the space. When installed externally, light shelves also provide shading by blocking solar radiation from entering through the lower part of the window [11]. The lower part acts as a viewing area typically paired with curtains, blinds, or other privacy mechanisms.

Several recent research works have investigated the concept of balancing thermal and daylight requirements, using different definitions to describe its overall objective [12-15]. The body of work in this field generally supports the conflicting nature between thermal insulation and daylight access. For instance, Altan *et al.,*'s [12] study evaluated how façade thermal insulation layers impact both heat losses and solar gain reduction while also limiting interior daylight access. Similarly, Atzeri *et al.,*'s [13] study uncovered similar behaviour by examining various glazing systems paired with shading control strategies for achieving a balance between thermal performance and natural lighting availability. In general, most studies discussed the potential achievement of thermal daylight balance through simultaneous optimization of both objectives within building designs. Moreover, the research regarding thermal daylight balance covered various locations and climates around the world. However, a recent review by Yu *et al.,* [5] highlighted that equatorial climates have been relatively understudied despite receiving abundant sunlight and facing thermal daylighting challenges. While buildings in this region face intense solar heat gain, there is potential for passive daylighting design which has not been fully utilized according to Yeh *et al.,* [16]. Integrating climate-responsive design strategies can enhance the sustainability and resilience of tropical buildings in the face of climate change impacts, contributing to more comfortable living and working environments and lessening the buildings’ environmental footprint [17]. Therefore, this study will focus on investigating the daylighting and thermal balance concept in the tropical region by examining the sensitivity of design parameters towards daylight and thermal energy performance. This paper aims to study the impact of climate change on building design parameters and light shelf parameters in terms of daylight and energy performance.

2. Methodology

To maximise daylight and achieve energy efficiency in a building, it is imperative to assess its performance starting from the initial design phase. Design parameters such as orientation, space area, floor-to-floor height, and fenestrations are critical for daylighting and energy efficiency, and they need to be considered in the early design stage as these parameters are difficult to change later [18,19]. For this reason, the study aims to identify the influence of design parameters which are critical during the early design stage. This helps the designers to understand its behaviours and will aid designers in decision-making during the early design stage.

2.1 Parametric Model

A parametric modelling approach was used to generate and evaluate various design alternatives. Parametric design involves the use of parametric modelling software and algorithms to explore design options by varying input parameters. Parametric design has been widely used in architectural design to optimise building performance, as it allows for the simultaneous consideration of multiple design parameters and their impact on building performance [20].

In this study, the parametric model was developed using Rhinoceros 3D and Grasshopper, a visual programming interface for Rhinoceros [21]. The model was based on a case study of double-storey terrace housing in Malaysia. The intermediate unit of such housing was chosen because based on our initial study, the ground floor of such housing faced a limited daylight entry, hence often incurring additional artificial lighting during the day. A typical double-storey terrace housing in Malaysia has 3 to 4 bedrooms with a typical frontage of 6 to 8 meters and a depth of 10 to 13 meters [22]. In this study, the parametric model was built for the most problematic area which is the open living and dining located on the ground floor of such a house. This area has limited access to windows area and often has a deep floor area. The deep floor plans of such space hinder the achievement of uniform daylight distribution throughout the interior space [23]. Figure 1 and Figure 2 show the 3D Revit model of the case study and energy model developed in Grasshopper. Figure 3 portrays the floor plans and the section of the case study.

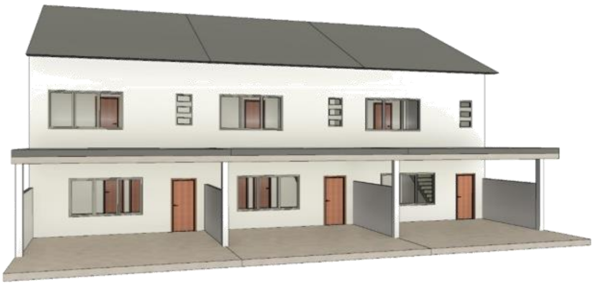


Fig. 1. The Revit 3d model of the case study

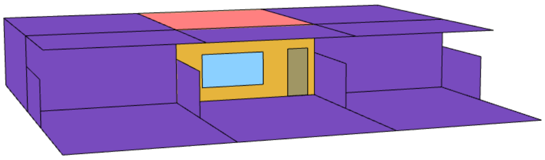
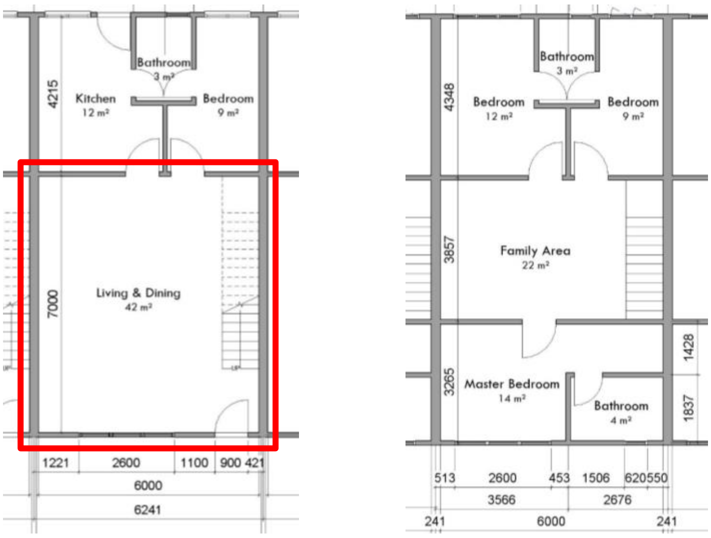


Fig. 2. The energy model developed in Grasshopper



Ground Floor Plan

1st Floor Plan

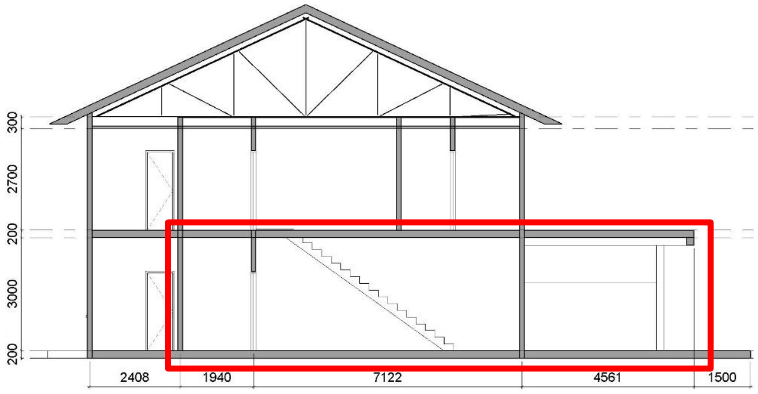


Fig. 3. The floor plans and section of the investigated house. The red outline indicates the space to be investigated

To investigate the influential design parameters during the early design stage, the parametric model includes room basic parameters such as orientation, room height, room depth, room width and window-to-wall ratio. Furthermore, to enhance the daylight and thermal condition of the room, design parameters that are related to the light shelf as daylight and shading device were also investigated such as shading depth, shade width, shade tilt angle and glazing transmittance. Figure 4 shows the design parameters investigated in this study. On the other hand, Table 1 outlines the minimum and maximum range of the design parameters investigated in this study. There was a total of 5.19+16 design alternatives investigated in this study.

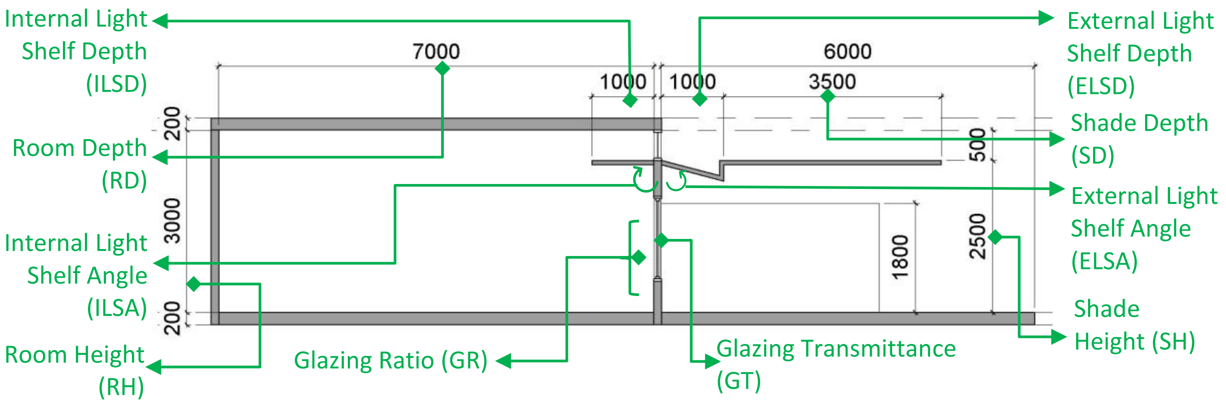


Fig. 4. The design parameters investigated in this study

Table 1
Range and steps of the input data used for the parametric modelling

Parameters	Min.	Max.	Steps	Counts	Units
Room Orientation (RO)	0	359	1	360	0 Degree from South (^{0})
Room Width (RW)	3.0	10.0	0.1	70	Meter (m)
Room Depth (RD)	3.0	10.0	0.1	70	Meter (m)
Room Height (RH)	3.0	5.0	0.1	20	Meter (m)
Glazing Ratio (GR)	0.1	0.9	0.1	9	Ratio (%)
Glazing Transmittance (GT)	0.1	0.9	0.1	9	Ratio (%)
Shade Depth (SD)	0.0	5.0	0.1	60	Meter (m)
External Light Shelf Depth (ELSD)	0.0	1.0	0.1	11	Meter (m)
Internal Light Shelf Depth (ILSD)	0.0	1.0	0.1	11	Meter (m)
External Light Shelf Angle (ELSA)	-15	45	1	61	Degree angle (^{0})
Internal Light Shelf Angle (ILSA)	-15	25	10	41	Degree angle (^{0})
The total number of design alternatives:				5.19+16	

2.2 Simulation Setup

The daylight simulation employed The Ladybug Tool version 1.5.0, a Grasshopper plugin utilising the Radiance engine [24]. The sensor grid had a 0.5m spacing at a 0.75m working plane height, with a 0.5m offset from interior walls to avoid peripheral measurements (Figure 5). The simulation was conducted annually under climate-based sky conditions. To account for artificial lighting during daylight hours, a schedule was established from sunrise to sunset. The occupancy schedule assumed weekday usage of 2 hours in the morning and 6 hours in the late afternoon/evening, weekend usage from 7 AM to 10 PM, and public holiday non-usage, with 22 public holidays recorded in Malaysia in 2022. Optimal radiance ambient parameters from previous research were assigned, as outlined in Table 2, with the default rcontrib parameters indicated in brackets. The reflective properties of modelled surfaces, such as light shelves, walls, roofs, and floors, were set to 0.9, 0.75, 0.8, and 0.2, respectively.

Table 2
Radiance ambient parameters for daylight simulation

Ambient bounces (-ab)	Ambient division (-ad)	Ambient super samples (-as)	Convergence threshold (-c)	Direct relays (-dr)	Direct pretest density (-dp)	Limit reflection (-lr)	Limit weight (-lw)
6	70000	(4096)	(1)	(3)	(512)	(8)	(4e-07)

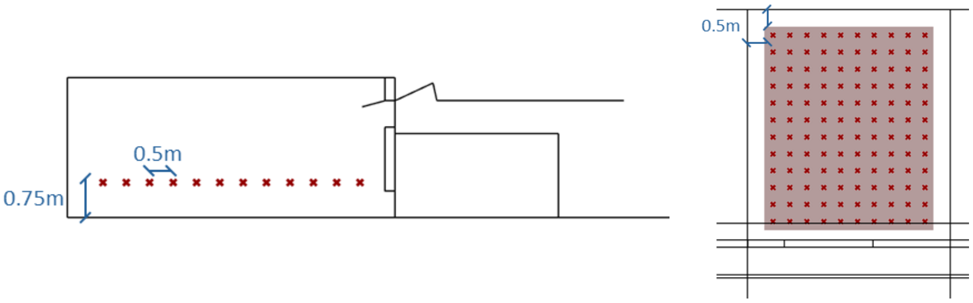


Fig. 5. The location of sensor points for daylight simulation

For the thermal energy simulation, the study employed OpenStudio version 4.5, a plugin integrated with Ladybug Tool version 1.5.0 [25]. The lighting and occupancy load schedules were consistent with those used in the daylight simulation. An occupancy of five individuals was assumed during occupied hours. Additionally, an equipment load of 41 watts per square metre was incorporated. All surfaces of the room were set as adiabatic, except for the front façade, which was designated as outdoor facing (Figure 6). The room was fully air-conditioned, with the cooling HVAC set points programmed to 24 degrees Celsius. Given the hot climatic conditions of the region, residential buildings typically do not have heating systems installed. To ensure that no heating was factored into the simulation, a lower-than-standard heating set point of 8 degrees Celsius was implemented.

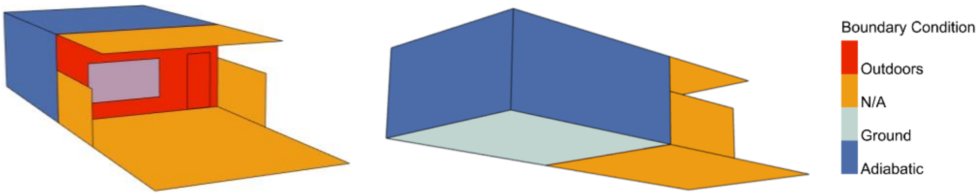


Fig. 6. The boundary conditions of the energy model

2.3 Metrics

To evaluate the performance of the parametric model, several metrics were used. Useful Daylight Illuminance (UDI) was used to measure the performance of daylighting. This metric provides information on the proportion of occupied time that the illuminance is within a useful range, typically between 100 and 2000 lux [26]. UDI values indicate the percentage of hours in a year when the illuminance levels on the horizontal working plane fall within specific ranges. In this study, the UDI ranges are divided into 3 bins: UDIs (below 100 lx) indicate the duration with insufficient illuminance and requiring supplementary electrical lighting for visual tasks; UDIa (100 lx to 2000 lx) defines the period where natural light is sufficient (autonomous) for tasks; and UDIe (more than 2000 lux) represents times when excessive daylight may cause overheating or glare issues. The ranges of these UDI bins were determined according to Malaysian Standards: Code of Practice on Energy Efficiency and Use of Renewable Energy for Residential Building (MS 2680:2017) [27]. Furthermore, according to the standard, the targeted UDI level for living and dining space for residential buildings should be 200 lux and 250 lux respectively.

This research also examines the daylight uniformity ratio (UR) as a measure for evaluating the distribution of daylight in each space. The uniformity ratio is calculated by dividing the minimum illuminance by the average illuminance [28]. A key focus is on the notable divergence in daylight levels due to narrow and deep floor plans, particularly evident in intermediate units with windows only on their front and back sides. Consequently, living-dining areas situated at the front of such units encounter limited exposure to natural light, amplifying dependence on artificial lighting during daytime hours and leading to increased energy consumption.

The total annual energy consumption is another metric to evaluate the performance of the parametric model. This metric provides the total annual energy use of the building, including the energy needed for lighting, and cooling. In this study, three energy metrics were employed to analyse the energy efficiency of the parametric model: annual cooling energy use per square meter (CLE), annual lighting energy use per square meter (LTE), and annual solar gain energy per square meter (SGE). The unit of measurement is kilowatt-hours per square meter per year (kWh/m^2).

2.4 Weather Files

The simulations were performed in three Malaysian cities: Kuala Lumpur, Bayan Lepas, and Kota Bharu. The selection of these cities was based on the availability of weather data from the EnergyPlus database. These areas experience a tropical wet climate characterised by constant moisture and year-round rainfall, by the Köppen-Geiger climate classification [29]. To investigate the impact of solar heat gain in tropical regions due to global climate change, the research also examined future hourly weather data for the locations under study. The International Weather for Energy Calculation year from the weather stations of the three cities was used as a reference for the current climate conditions. The CCWorldWeatherGen tool, developed by researchers at the University of Southampton, was utilized to analyse the future climate projections for the cities of Kuala Lumpur, Bayan Lepas, and Kota Bharu [30]. This tool employs morphing methods to convert standard meteorological data into new weather files projecting conditions for the 2020s, 2050s, and 2080s [31]. The CCWorldWeatherGen tool employed the HadCM3 global circulation model from the Emissions Scenarios, which describes six distinct climate change scenario families: A1F1, A1B, A1T, A2, B1, and B2 [32]. For this study, the morphed tool defaulted to using the A2 climate change scenario as its basis.

2.5 Model Calibration

To validate the simulation model's accuracy, it was calibrated against the measured energy data from a study by Ahmed *et al.,* [33]. The equipment loads and occupancy schedules for the calibration process were based on the details provided in the referenced study. According to Ahmed *et al.,* [33] the typical monthly energy consumption for a two-storey terraced house in Malaysia is 920 kWh. A total of 14 model variations were calibrated, with the final variation achieving a percentage difference of less than 10% from the measured data. This calibrated model was then employed to assess the influence of design parameters on daylight and energy performance.

2.6 Sensitivity Analysis

This study used global sensitivity analysis, particularly the enhanced Morris Method or Elementary Effect technique, to determine the most significant design parameters influencing energy and daylight performance in buildings [34-37]. The Morris approach is a reliable way to assess the prioritisation of impacts, even when the model exhibits non-linear patterns, as is common in energy and daylight models [38,39]. For this investigation, 20 trajectories and 4 levels were employed, generating 240 samples for each climate scenario. The sample size was calculated using an equation, where D represents the number of input parameters and k indicates the number of trajectories [40].

All procedures for the Morris sampling and sensitivity analysis were executed in Python 3 using the SALib module version 3 [41].

$$n = k(D + 1) \tag{1}$$

3. Results and Discussion

The objective of the sensitivity analysis was to determine the most significant parameters and their influence on the output metrics. The sampling procedure, conducted using the Morris method, involved selecting four values for each of the 11 parameters. This approach employs a one-factor-at-a-time technique to organise the simulation runs, whereby each parameter is assigned one of four values, and successive runs differ from previous ones solely by altering one value at a time. According to Eq. (1), there were a total of 240 simulation samples performed. Figure 7 and Figure 8 show an example of how the simulation of the Morris method takes place for one of the studied locations (Kuala Lumpur). The figure illustrates the behaviour of the considered metric when facing a changing climate scenario for all 240 simulations. Figure 7 shows the input variables allocated to the model for each simulation run using the original Morris sampling method, following the sequence in which they were produced by the random algorithm. Figure 8 shows the corresponding output values for the investigated metrics, starting from useful daylight illuminance (UDIs, UDIa, UDIe), uniformity ratio (UR), annual lighting energy use (LTE), annual cooling energy use (CLE) and solar gain energy use (SGE), for each simulation run. The dashed line in Figure 8 indicates the values of each metric in the future climate, while the straight line indicates the value of each metric in the present climate.

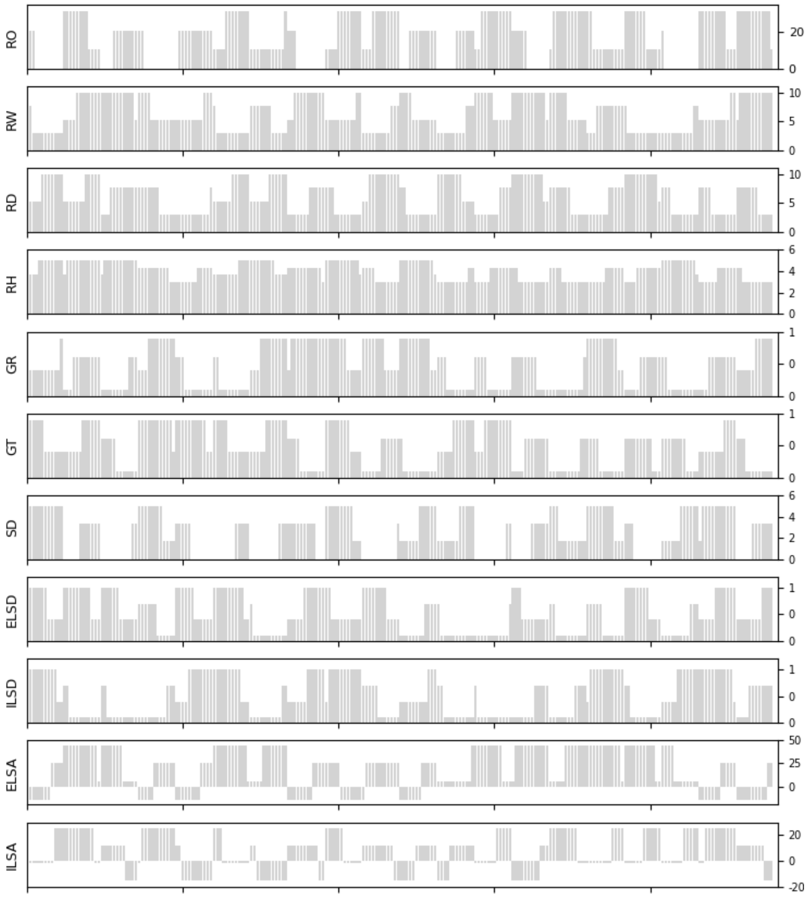


Fig. 7. The design parameters assigned for each simulation run

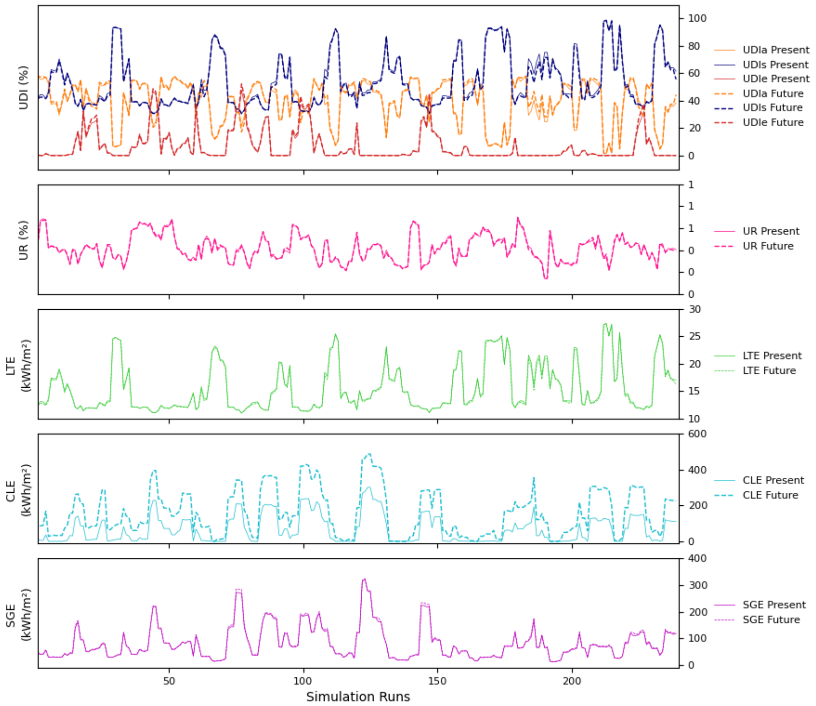
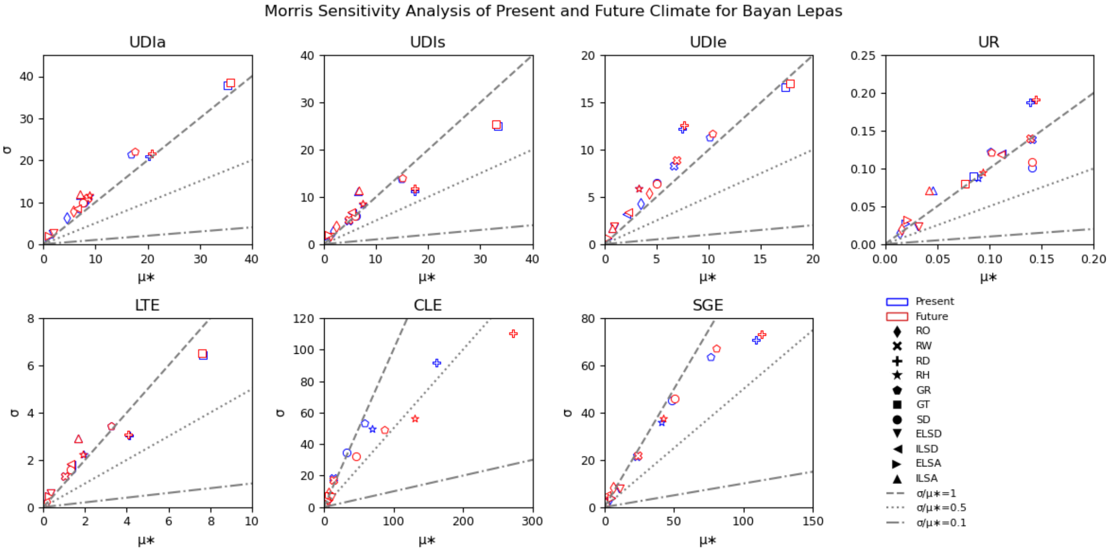


Fig. 8. The daylight and energy results for each simulation run

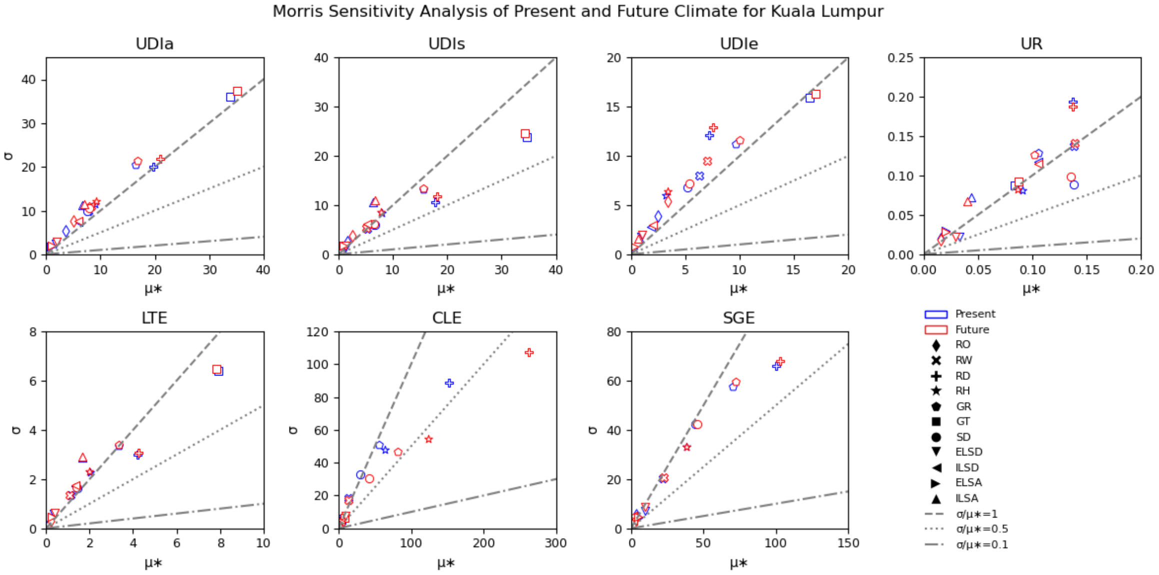
One of the key findings of this analysis was that the effect of changing climate scenarios was more pronounced for CLE, compared to the other metrics. The cooling energy use is relatively higher in the future climate, probably because it has a more direct and pronounced relationship with rising temperatures, a primary consequence of climate change [4]. On the other hand, while the other metrics are still affected, it is less directly impacted by the impact of climate change. It can be seen through the relatively small differences between present and future climates in UDI, UR, LTE, and SGE. These metrics are influenced by factors like cloud cover, solar altitude, and surrounding obstructions, which are affected by climate change but in less direct and predictable ways than temperature.

Figure 9 shows the monotonicity of the input parameters to the output metrics for KL, BL and KB respectively. The position of the input parameters relative to the three lines in the graph determines whether the relation is linear, monotonic or almost monotonic. If situated below the value of 0.1, their performance follows a linear pattern; if they fall within the range of 0.1 to 0.5, they exhibit monotonic behaviour; in the interval between 0.5 and 1, they display near-monotonic characteristics; beyond this range, they demonstrate high non-linearity and non-monotonicity behaviours [42]. The position of the input parameters from right to left indicates the importance of the parameters where the parameters that are located further to the right are more important than to the left. According to the findings presented in Figure 9, there is no linear correlation between the input parameters and the output metrics across the three cities. The behaviour of the input parameters is highly consistent across the three locations. For thermal energy performance metrics, such as cooling energy use and solar heat gain, most of the influential parameters exhibit either monotonic or near-monotonic relationships. This suggests that an increase in the parameter value leads to a proportional rise in the corresponding metric, while a decrease results in a correlated but not directly proportional decline.

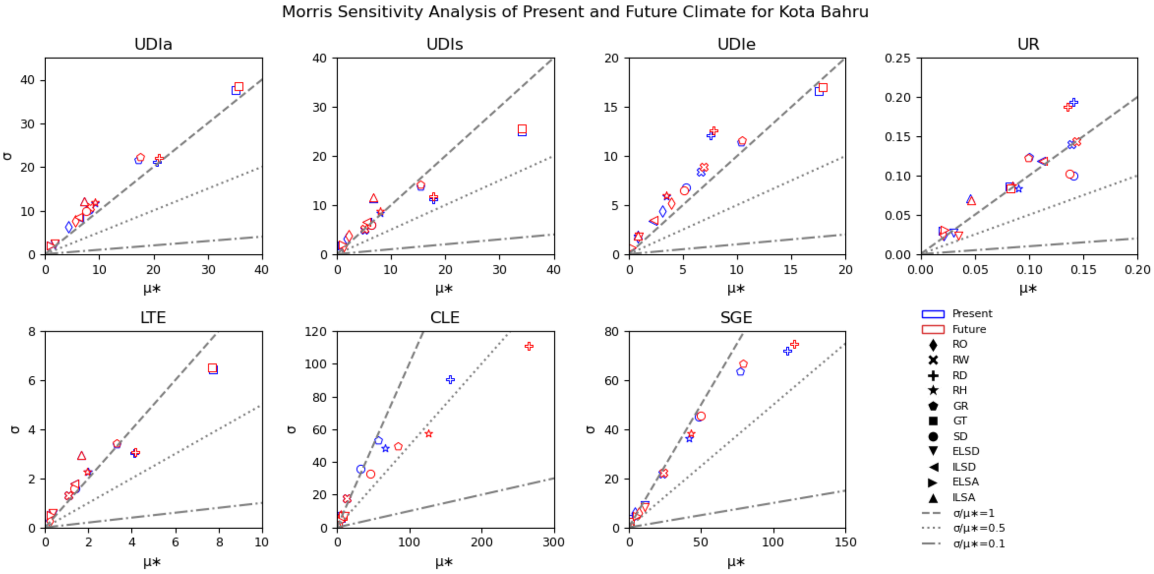
In the case of daylight-related metrics such as UDI, uniformity ratio (UR) and lighting energy use (LTE), the parameters get further from monotonicity. This implies that a change in a parameter might not always have a proportional or predictable effect on daylight levels. For instance, increasing the window-to-wall ratio size might increase daylight up to a point, but then lead to overheating and require shading, reducing daylight again [43]. Moreover, for UDI metrics, important factors deviate from monotonicity due to high illuminance instances outside the expected range. When input factors contribute to illuminance rising above 2000 lux, the effect on the metric is a reduction in percentage rather than an expected increase [42].



(a)



(b)



(c)

Fig. 9. The Morris sensitivity analysis for (a) Bayan Lepas, (b) Kuala Lumpur, and (c) Kota Bahru

Figure 10 summarizes the ranking order of the input parameter for each city in present and future climate. The input parameter ranking was given by the absolute value of u* calculated by Morris's sensitivity analysis. In general, the ranking of parameters for each city is relatively consistent. The pattern seen was suggestive of the similarity of the climate in each city. Furthermore, the varying climate conditions in the future do not impact the order of the ranking. Generally, room depth (RD) has emerged as an important input parameter for terrace housing in Malaysia, followed by glazing ratio (GR) and glazing transmittance (GT). While external light shelf angle (ELSA), external light shelf depth (ELSD) and room orientation (RO) have a lesser impact on daylighting and thermal energy performance. To understand further the impact of the input parameters on daylight and thermal performance specifically, the ranking of input parameters for each metric category is separated in Figure 10. Since the behaviour of the input parameters is very similar in each city, Figure 11 only represents the overall and specific ranking of input parameters for the Kuala Lumpur city. In this diagram, the ranking of the input parameters for daylight-related metrics is slightly different from the thermal energy metric. One of the key observations here is that although room depth (RD), glazing ratio (GR) and glazing transmittance (GT) were ranked higher in the overall ranking, the glazing transmittance was ranked lower for thermal energy metrics which signifies lesser importance. It is most likely attributed to the behaviour of GT that directly dictates how much visible light passes through the window and enters the space [44]. While GT may influence the solar heat gain of the space, other factors such as the U-value and solar heat gain coefficient (SHGC) of the glazing might play a more significant role in heat transfer into the space [45]. Another significant comparison between daylight and thermal energy ranking is ranking for room height (RH). RH was ranked higher for thermal energy metrics compared to daylighting metric which might be attributed to the direct relation of the volume of air to be conditioned to cooling energy [46]. More energy is required to change the temperature of a larger volume of air. While a higher room might initially seem to allow more daylight, the illuminance at the working plane, which is how UDI is measured, might not be significantly different from a lower-height room [8].

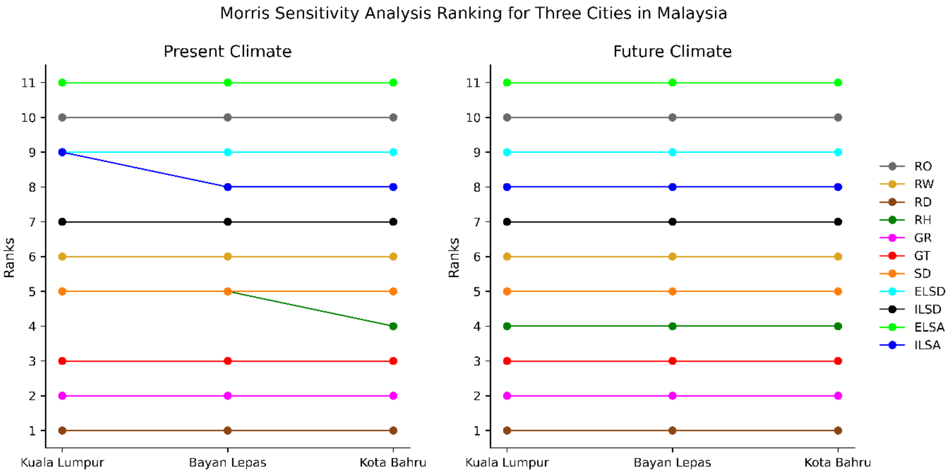


Fig. 10. The overall ranking of input parameters for the studied locations

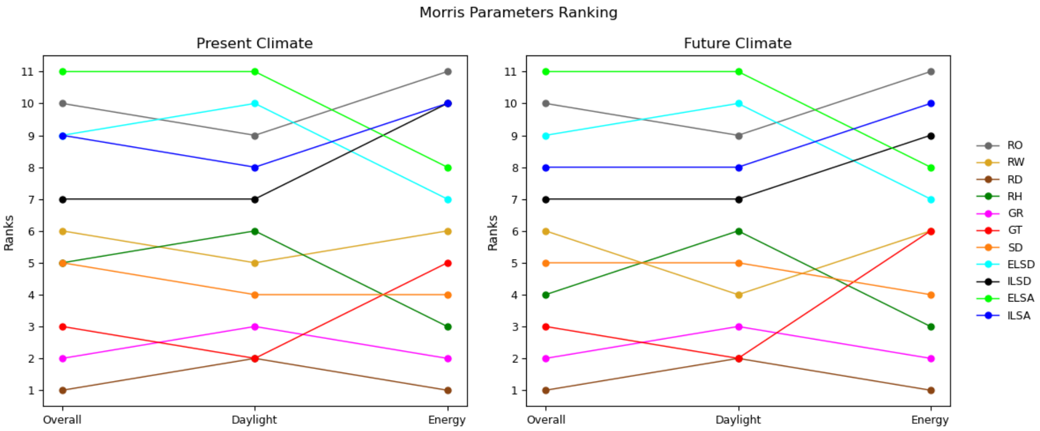


Fig. 11. The ranking of input parameters for daylight and energy-related metrics

The observation from the result of the sensitivity analysis for the lower-ranked parameters showed an interesting finding. 5 input parameters have been consistently ranked in the lower range for both daylight and energy metrics which are internal light shelves angle (ILSA), internal light shelves depth (ILSD), external light shelves depth (ELSD), external light shelves angle (ELSA) and room orientation (RO). The low influence of RO on daylight and energy metrics in tropical climates is expected since the tropical regions receive relatively consistent sunlight and temperatures throughout the year, unlike higher or low latitudes regions where the seasonal sun's angle and the temperature vary significantly. Furthermore, relatively small differences were found in terms of the ranking of external and internal light shelves concerning daylight and energy metrics. The external light shelf parameters (ELSD and ELSA) seemed more sensitive to thermal energy metrics while the internal light shelf parameters were more sensitive to daylight metrics. This may be explained by the function of the light shelves. Internal light shelves are positioned inside the building, typically above eye level. Their primary function is to reflect direct sunlight deeper into the room, improving daylight penetration and distribution. Because they are located inside, internal light shelves may have a negligible impact on the building's thermal energy performance as they don't directly interact with the building envelope to affect heat gain or loss [47]. Additionally, external light shelves can act as a shading device by shading windows from direct solar heat gain thus impacting the thermal energy performance of the space [48]. In the case of climate change's impact on daylight and thermal energy performance, it can be noted that the order of influence of the parameters is minimally affected by different climate scenarios. A slight difference is noticed in the ranking of shade depth (SD) and room width (RW) for daylight metrics in the future climate. In the future climate, RW is ranked higher than SD for daylight-related metrics compared to the present climate. In short, the findings of this study highlight the crucial role of sensitivity analysis when investigating thermal-daylight balance. It helps designers explore the complex relationships between input parameters, identify potential trade-offs, and make informed decisions to achieve a balance between daylighting benefits and thermal performance aspects.

4. Conclusion

The findings presented here are part of a wider study which is believed to be the first systematic comparison of several design parameters that are critical for the early design stage for the tropical region. The results of the Morris sensitivity analysis provide valuable insights into the relative influence of various design parameters on the daylight and thermal energy performance of terrace housing in Malaysia, considering both present and future climate scenarios. The analysis identified room depth, glazing ratio, and glazing transmittance as the most influential parameters for both daylighting and thermal energy metrics. Room height was also found to be an important parameter, particularly for thermal energy performance.

On the other hand, parameters such as internal and external light shelves, and room orientation were consistently ranked as less influential. These findings can inform the early-stage design process for terrace housing in Malaysia, helping architects and designers prioritize the most critical parameters to achieve optimal daylight and energy performance. Moreover, the study's approach of separating the ranking of input parameters for daylight and thermal energy metrics provides a deeper understanding of the unique behaviour of these parameters in the tropical context. This knowledge can be utilized to develop more nuanced design strategies that balance the competing demands of daylighting and thermal energy efficiency in the tropical region.

In addition, the assessment of climate change's impact on the relative influence of design parameters underscores the importance of considering future climate scenarios in the design process. Although the impact of climate change on daylight and thermal energy metrics is expected, the relative ranking of design parameters is generally maintained, suggesting that the design recommendations derived from the present-day analysis would still be valid in the future climate.

Future research could expand on this work by investigating the interactions between influential parameters, as well as exploring optimization techniques to identify the most suitable design configurations for terrace housing in Malaysia. Additionally, further research could focus on expanding the scope of the study to include other building typologies and geographical locations, thereby contributing to a more comprehensive understanding of the influence of design parameters on building performance. Overall, the methods and findings presented in this study can serve as a valuable resource for guiding sustainable design decisions for residential buildings in the tropical region, particularly during the critical early design stage [49].

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