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The Impacts of Passive Design Strategies on Building Indoor Temperature in Tropical Climate

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ABSTRACT

Traditional buildings in Malaysia were developed for hundreds of years to respond to the local climate. Occupants can comfortably occupy the traditional buildings without a mechanical system such as an air conditioning system. However, in many modern buildings, whether houses, mosques or shophouses, similar traditional strategies are not extensively adopted; thus, they are very dependent on the mechanical system to achieve good thermal comfort. Therefore, this study aims to investigate the effect of selected passive cooling strategies on the indoor temperature of a building in a tropical climate. The methodology adopted in this study was computer simulation validated with measured data from a selected case study. The thermal comfort of a case study was examined with different passive cooling strategies that were applied using IES-VE 2019 building simulation software. The simulation was conducted for various design strategies, such as adding shading devices and closing the curtains to decrease the amount of solar radiation that enters the house from the windows, using timber for walls and clay tiles for the roofs and examining seven different orientations to find the best strategy for the house. All these strategies were tested and compared between full-day natural ventilation and without any ventilation. The thermal comfort of these strategies was graphically defined based on the operative temperature. The results of this study revealed that protecting the windows from solar radiation by adding shading devices and closing the curtains had the lowest indoor operative temperature achievement compared to other examined strategies.

Keywords: Building simulation, double storey house, IES-VE software, indoor temperature, shading devices, thermal comfort, timber walls

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INTRODUCTION

Based on modern buildings' current design, occupants must use an air-conditioning system to get thermal comfort. Moreover, the affordability of the mechanical system leads to the perception that designing a building for thermal comfort is less important compared to its aesthetic and cost factors because thermal comfort issues can always be resolved during the occupancy period by installing an air conditioning system, which is now affordable and easily installed as shown in Figure 1. Low electricity tariffs in Malaysia support this trend of controlling indoor thermal comfort. Increasing the use of air conditioning systems with increasing building development in developing nations such as Malaysia will lead to a huge demand for electricity. As Malaysia is still mainly depending on fossil fuels for electricity (Latif et al., 2021; Basri et al., 2021), this will lead to a negative impact on the environment due to factors such as global warming, carbon dioxide emission and air pollution (Imran et al., 2018; SEforALL, 2020; Shafique & Kim, 2017).

Figure 1 shows examples of low-rise and high-density low-cost development in Malaysia, normally occupied by low-income families. Though occupied mostly by low-income families, it is very common to find compressors installed on the façade of the buildings. It is due to various factors such as affordable electricity tariffs as well as less acceptable indoor thermal comfort. Less acceptable indoor thermal comfort in low-cost housing, either low- or high-density housing, is very common as the result of design and cost factors (Amir et al., 2019). For example, greater sun heat penetration is due to poor orientation of the building, unprotected opening and the use of materials, such as sand brick and metal decking.

As the climate change issue becomes critical, the building industry shall look at various strategies to reduce the negative impact of the building sector on the environment. One of the many solutions is to promote buildings with good passive cooling strategies that could contribute to good indoor thermal comfort and are less dependent on mechanical

Figure 1. Single story, low-cost detached house with metal decking roof and plastered sand brick wall (Amir et al, 2019) (left), and high-density low-cost housing with air conditioning compressor on the facade (right)

cooling, such as air conditioning systems (Yusoff & Ja'afar, 2019; Yusoff & Mohamed, 2017; Yusoff, 2020). In addition, a lot can be learned from traditional or heritage buildings in Malaysia, whether houses (or palaces), shophouses or mosques.

Traditional buildings in Malaysia have been developed by local builders for hundreds of years and have been responding well to the local climate with various cooling strategies such as large openings (Yusoff & Ja'afar, 2019; Yusoff, 2020). Therefore, traditional buildings, such as houses, shophouses and mosques, do not require mechanical systems such as air conditioning to obtain acceptable indoor thermal comfort. The strategies adopted in these buildings include aspects related to opening, wall, roof, and shading. For example, it is common for traditional mosques and houses in East Cost Malaysia, such as Kelantan and Terengganu, to use thin clay tile known as *singgora* (Husen & Mohamed, 2021) that only store a small amount of heat, which avoids poor indoor temperature during night-time. Using timber as a material also contributes towards good indoor thermal comfort during night-time due to its materiality that does not store heat.

Figures 2, 3, and 4 show some traditional buildings, which are well designed for indoor thermal comfort through various strategies. Generally, it can be clearly observed that the buildings are well ventilated with various strategies. For example, the mosque in Figure 2 shows a large area of openings around the indoor praying area, allowing for good cross ventilation. In the case of a Malay traditional house in Kelantan (Figure 2), fixed decorative openings are provided on a wall for natural ventilation. In the case of the shophouse, Figure 4 shows a shophouse in Malacca City, which has an internal courtyard to solve the ventilation limitation for the long plan intermediate two-storey shophouses. Therefore, the internal courtyard allows for natural ventilation and lighting in the indoor spaces. The internal courtyard of a heritage shophouse could lead to better indoor thermal comfort (Kubota et al., 2014). Some heritage shophouses in Malacca City have more than one internal courtyard. Multiple internal courtyards allow natural lighting and ventilation

Figure 2. Exterior (left) and interior (right) of Kampong Laut Mosque, Kelantan (Mohamed, 2020)

Figure 3. Exterior (left) and interior (right) of Malay traditional house of Kelantan (Mohamed, 2020)

Figure 4. Exterior (left) and interior (right) of heritage shophouse in Melaka City

in a double-storey linked shophouse with a very long depth. More than 200 feet in depth are very common in such heritage shophouses in Malacca City. However, nowadays, such a deep plan is not common in modern linked shophouses.

Other than strategies for natural ventilation and lighting in traditional buildings, many other factors influence the indoor thermal comfort of the buildings—for example, the materials used for the wall and roof. For the traditional Malay house, as in Figure 3, the roof material is thin clay tile known as Singgora, and timber is used for the wall. In the case of the shophouse, as in Figure 4, the roof's material is clay tile, and a thick brick wall is used for the wall. In the case of a traditional mosque (Figure 1), the materials are similar to the traditional Malay house as in Figure 2. However, there are also old traditional mosques in Malaysia that use thick brick walls, such as in Malacca City. The clay tile, timber walls and thick brick walls with a combination of good design strategies in the traditional buildings, such as internal courtyard, large opening, and deep roof overhang, could contribute to better indoor environmental quality (Kubota et al., 2014, Yusoff & Ja'afar, 2019; Yusoff, 2020; Rana et al., 2021)

Nowadays, in many modern buildings, whether houses, mosques or shophouses, similar traditional strategies are not extensively adopted; thus, they are very dependent on the mechanical system to achieve good thermal comfort (Figure 5). Nevertheless, various sustainable or green strategies in traditional buildings can be learned and applied in a modern buildings, leading to greener architecture. In contrast to 'active' mechanical cooling devices, passive cooling is typically considered a combination of natural processes and approaches for lowering indoor temperatures (Prieto et al., 2018). Many studies (Mohamed, 2020; Husen & Mohamed, 2021; Oleiwi & Mohamed, 2021; Yusoff, 2020; Yusoff & Mohamed, 2017) have been conducted to identify, outline, or analyse the strategies in traditional buildings. Other than the strategies typically found in traditional buildings, many other passive green strategies are commonly found in modern buildings, such as the introduction of insulation in the roof, roof ventilator and low-emissivity glass. In addition, building designs and methods considering energy consumption can reduce cooling loads (Yeganeh, 2020). The study of Gamero-Salinas et al. (2021) underlined the need for passive cooling and overheating prevention design solutions in tropical regions.

Indoor overheating can be reduced in the tropics if proper building design principles for these climate zones are used (Bhikhoo et al., 2017). Climate change and economic growth will raise cooling energy demand in this region, necessitating immediate adaptation in the building sector to decrease the problems posed by the future rise in cooling energy demand and the increased climatic changes (Santamouris, 2016).

Mirrahimi et al. (2016) conducted a review of prior research on the impact of building envelopes on energy consumption and thermal performance in Malaysia. The study found that passive cooling strategies successfully decreased energy consumption for hot-humid tropical building envelopes. In addition, the study found a substantial link between several architectural components, such as shading devices, external walls, external roofs, external glass, and insulation, and lowering the energy consumed for cooling.

Figure 5. Modern mosque at Cyberjaya, Malaysia, has a large opening to optimise natural ventilation and lighting

However, for this study, the investigation was only conducted on a few selected strategies that could potentially affect indoor thermal comfort. Two of the selected strategies are the introduction of shading devices (external) and curtains (internal). Other than that, comparisons were made between a brick wall and timber for wall materials, the clay and concrete tiles for the roof and, finally, the various orientation of the buildings to understand the effects of solar heat. Therefore, this study aims to investigate the effect of the application of selected passive cooling strategies on the indoor temperature and thermal environment of a building located in a tropical climate.

It has been proved that thermal comfort can occur in a narrow range of body temperatures, and the skin moisture is kept low with minimum physiological effort (ASHRAE, 2017). However, occupants in naturally ventilated buildings have a wide range of comfort temperatures, which may exceed the limitations of ASHRAE Standard 55, and a response to local outdoor climate changes (Brager & de Dear, 2000). According to the study of Oleiwi (2020), after calculating the thermal acceptability limits based on the adaptive comfort standard (ACS) that was proposed by Brager and de Dear (2000), it is found that the maximum and minimum temperatures that should not be exceeded are 29.9 and 24.9 °C for 90% acceptability limit and 30.9 and 23.9 °C for 80% acceptability limit respectively in Bangi, Malaysia for April.

It is good to mention that this study only focuses on the aspect of operative temperature and does not look at the other aspects of thermal comforts, such as humidity and air speed. Furthermore, while there are various types of traditional buildings in Malaysia, as an initial study, the investigation was only completed on a double-storey building, which was purposely constructed as a test building for various research.

METHODOLOGY

Studies proved that the energy prediction process could anticipate cooling loads and the effect of passive cooling on lowering interior temperature gains with fair accuracy (Olawale-Johnson et al., 2021). In this study, several design strategies were applied to the tested house (reference case) to investigate the effect of these strategies on the internal thermal environment. The investigation was conducted and compared under two conditions: fully ventilated and without ventilation. Natural ventilation has been proven to be a good strategy to cool the interior spaces down in the tropics; however, allowing the hot air that comes from outdoor to enter the buildings could heat the structure and decrease thermal comfort (Kubota et al., 2009; Oleiwi, 2020). Figure 6 shows the methodology of this study.

The selected approaches are as follows:

(a) Adding external shading devices and closing the curtains inside the rooms to protect the windows from direct solar radiation.
(b) Using timber as a construction material for the walls and clay tiles for the roof

to investigate the effects of these materials with different thermal transmittance (U-value).

(c) Changing the orientation of the house by examining the other seven orientations to find the most thermal comfort orientation.

The tested house was located at the Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia (UKM), Bangi, 27 km from Kuala Lumpur, Malaysia's capital city. Figure 7 shows the double-storey house built using common modern construction materials (sand brick and cement for the walls and concrete roof tiles for the roof). This house was built purposely for research activities. Therefore, easy access to the house enabled the researcher to enter the house easily for site investigation. All the walls were not insulated for heat transmission. The wall structure consists of 114 mm thick sand brick with 19 mm thick cement plastering on the interior and exterior sides. The roof structure consists of concrete grey roof tiles

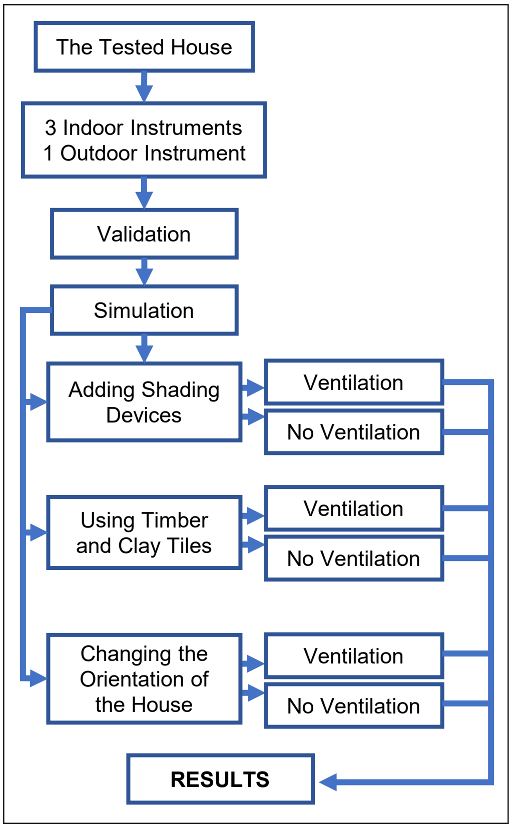


Figure 6. Research methodology diagram

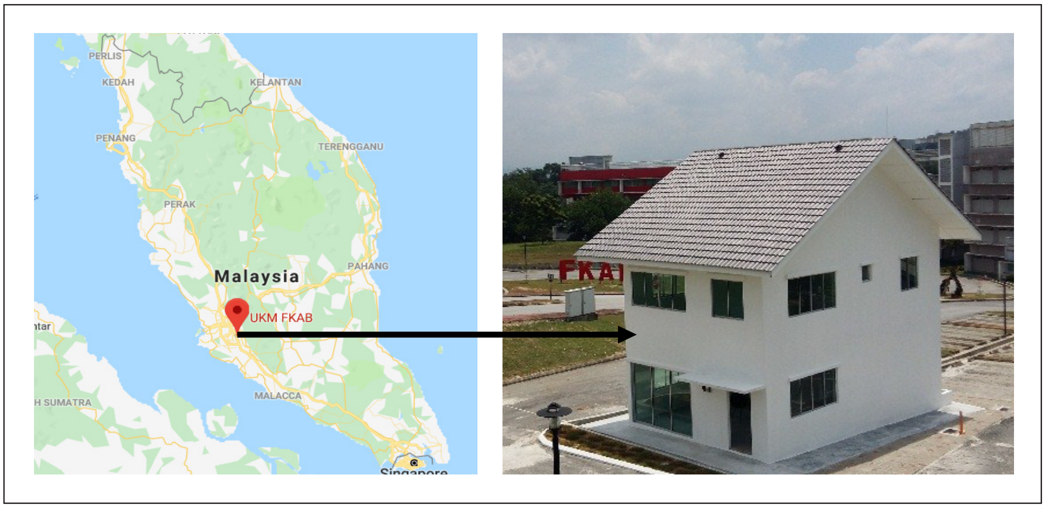


Figure 7. The tested house

with metal roof trusses with double-sided aluminium sisalation and a layer of 3.2 UCO Superflex soffit all around the roof.

The house includes a living room, kitchen, and a bathroom on the ground floor, and three bedrooms and two toilets on the first floor. In this study, Room 1 refers to the living room, Room 2 refers to the secondary bedroom, and Room 3 refers to the master bedroom. The windows of the house faced four directions. Figure 8 shows the ground and first-floor plans of the tested house.

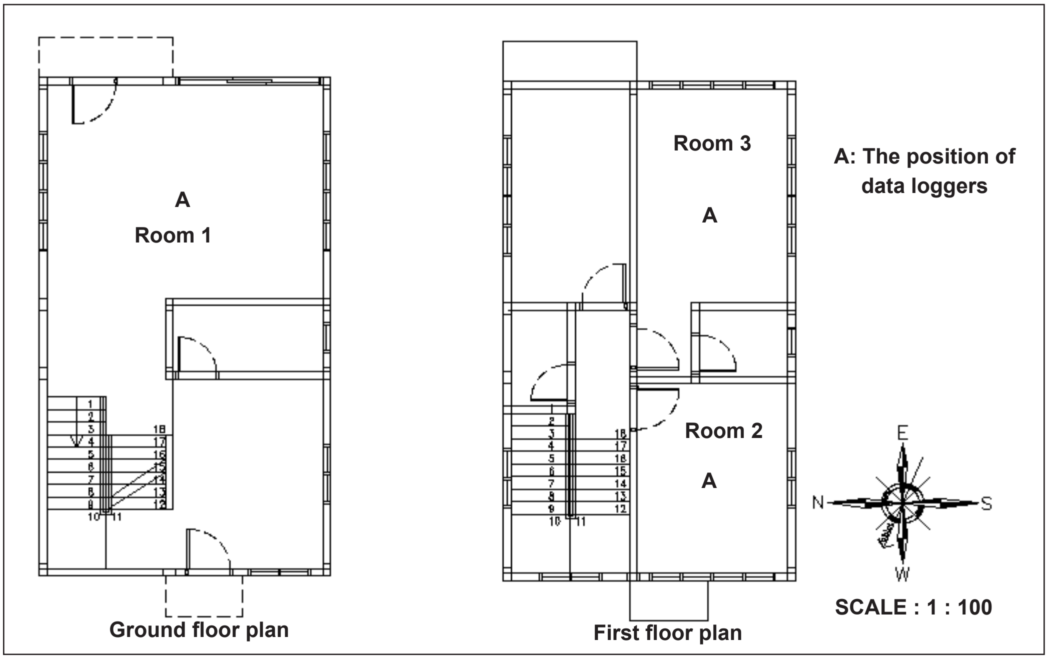


Figure 8. The plans of the tested house

Three sets of Delta Ohm HD32.3 WBGT-PMV thermal comfort instruments were placed indoors, in the centre of the living room (Room 1), the secondary bedroom (Room 2), and the master bedroom (Room 3). The third bedroom was not investigated. The instruments were positioned at 1.5 m above the ground to record the values of air temperature (Ta), relative humidity (RH), and mean radiant temperature (Tmrt) in each room. The data for each room was recorded and obtained using the software DeltaLog10 version 1.30. The list of all instruments is shown in Table 1.

The instruments were set to record data at 10-min intervals for 24 h. The selected measurement periods were from 1 April to 7 May 2018, which falls in the hottest period in the year in Malaysia based on the average monthly data of temperature for 11 years (MMD, 2017; Sulaiman, 2017). Moreover, the rainfall recorded by the MK-III Weather Stations™ was useful for determining whether each day was sunny or rainy. Rainy days were excluded from the study as they do not represent overheated days.

Table 1
Summary of instruments involved in this study

Instrument	Parameter	Unit	Range
	A- Indoor parameters		
AP3203.2 prop, Delta Ohm HD32.3 PMV data logger	- Air temperature (°C)	3	Temperature 0 to 100 °C
	- Air velocity (m/s)		Airspeed 0 to 5 m/s,
TP3276.2 prop, Delta Ohm HD32.3 PMV data logger	- Global temperature (°C)	3	-10 to 100 °C
HP3217.2 prop, Delta Ohm HD32.3 PMV data logger	- Air temperature (°C)	3	Temperature -10 °C to 80 °C
	- Relative humidity (%)		The relative humidity is 5% to 98%
	B- Outdoor parameters		
MK-III Weather Stations™	Air temperature (°C)	1	-55 to 85°C
	Wind speed (m/s)	1	0 to 67 m/s
	Relative humidity (%)	1	0 to 100%

The geometry of the computational model for the tested house was created using the IES-VE (2019) software. First, the building's geometry, dimensions, and areas of solid and transparent surfaces were defined using [ModelIT]. Next, the location of the house was defined by [APlocate], which was set as Kuala Lumpur suburbs as it was the nearest to the site. Next, window and door openings profiles and window types were set using [MacroFlo]. Then, fabric materials, thermal properties and simulation time were defined using [Apache]. Table 2 shows the construction materials used in the simulation of the tested house.

The simulation was done in the same period of the year of the selected site measurement periods. The weather data of this study were provided by IES-VE, which can be determined according to the nearest location.

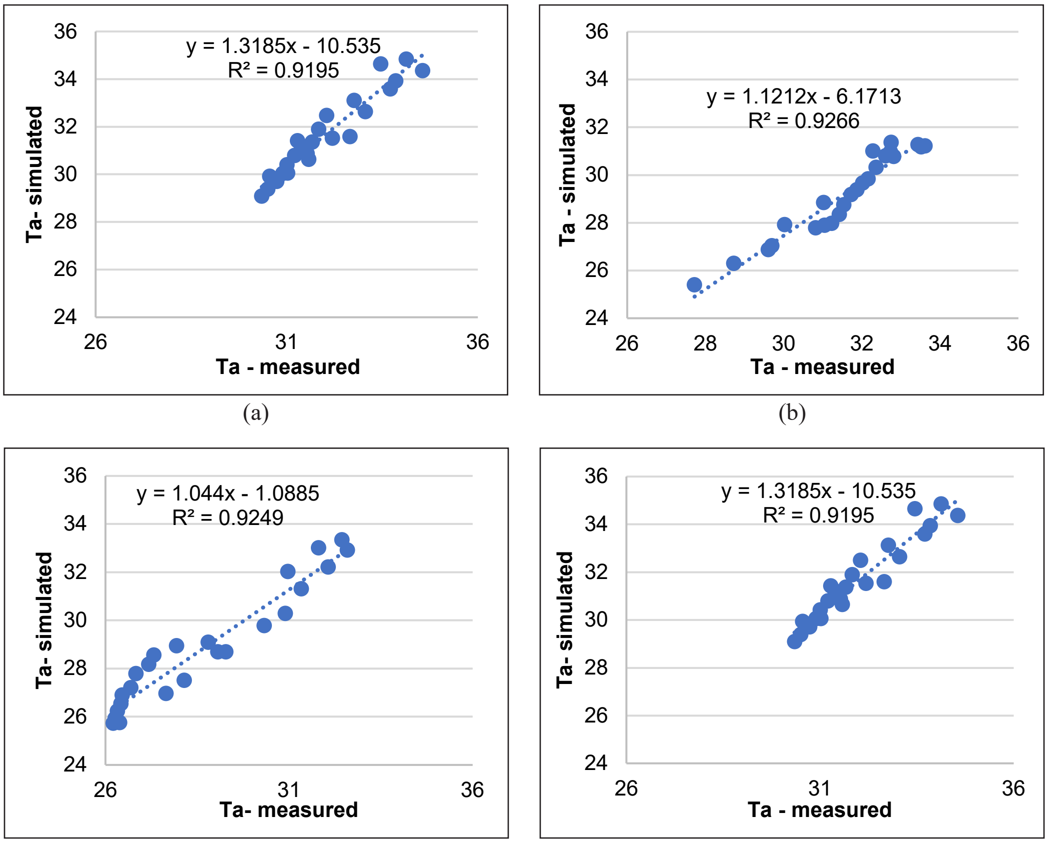
Table 2
Details of construction materials for the tested house. The values are the standard values in the software

Element	Construction	U-Value (W/m^2 k)
External walls	Cement plaster (19 mm), sand brick with cement (114 mm), cement plaster (19 mm)	3.4
Internal walls	Cement plaster (19 mm), sand brick with cement (114 mm), cement plaster (19 mm)	3.4
Roof (concrete tiles)	Concrete tiles (5 mm), aluminium sisalation (1 mm), UCO Superflex ceiling board (3.2 mm)	6.9
Roof (clay tiles)	Clay tiles (5 mm), aluminium sisalation (1 mm), UCO Superflex ceiling board (3.2 mm)	6.85
Floor	Cast concrete (220 mm)	3.6
Doors	Plywood	2.2

IES-VE simulation software has been chosen for this study as it permits the user to change construction materials, dimensions, thicknesses for all house components (roof, ground, and walls), and windows opening profile.

Before using any building simulation software, the validation of the simulated data should be evaluated by comparing the simulated data with the measured data (Oleiwi et al., 2019). In this study, the simulated indoor air temperature was compared with the one collected from field measurements (during the same period of the year) to ensure the accuracy of the simulation. The validated model would then be used for further simulation. As a result, it is found that the model of this study is valid because the correlation coefficient (R2) of the simulated with measured data was sufficient according to the recommendation of ASHRAE (2009) (R2 of 0.9 or greater), as shown in Figure 9.

To investigate the selected strategies that could affect indoor thermal comfort, firstly, 1-meter depth shading devices have been added above all the windows of the three tested rooms from outside. At the same time, other original conditions of the reference case



(a)
(b)
(c)
(d)

Figure 9. Linear regression analysis (measured versus prediction) for different ventilation conditions of: (a) full-day ventilation; (b) daytime ventilation; (c) night-time ventilation; and (d) no ventilation

remained. The simulation was done with full-day natural ventilation when all windows and internal doors were open for 24 hours and no ventilation when all windows and doors were closed for 24 hours separately. Then, closed curtains were added to the windows of the three tested rooms from the inside to the non-ventilated case to increase the protection of the windows from direct solar radiation.

Secondly, 20mm timber boards have been used as construction material for external and internal walls and flooring, while other original conditions of the reference case remained. Then, the concrete roof tiles were changed to clay roof tiles. Finally, both simulations were done separately with full-day natural ventilation and no ventilation.

Finally, seven orientations have been examined for the tested house, while other original conditions of the reference case remained- to find the most thermal comfort orientation of the house. Changing the orientation was done with full-day natural ventilation and no ventilation separately.

The main simulation output obtained from IES-VE was the indoor air temperature (T_a) and the mean radiant temperature (T_{mrt}) for the three rooms. The results were converted into Excel sheets to facilitate data analysis.

Operative temperature (T_o) was calculated based on Equation 1, which was proposed by ASHRAE (2010):

$$T_o = \frac{(T_a + T_{mrt})}{2} \qquad (1)$$

Where T_o is the operative temperature in °C, T_a is the air temperature in °C, and T_{mrt} is the mean radiant temperature in °C.

IES-VE was selected as it is software with a simple input interface that creates the prototype and modifies its layout. Moreover, the output can be easily interpreted and represented in tabular data or graphs. Finally, IES-VE is user-friendly, which makes this software useful for this study. A three-dimensional view of the building modelled in IES-VE is illustrated in Figure 10.

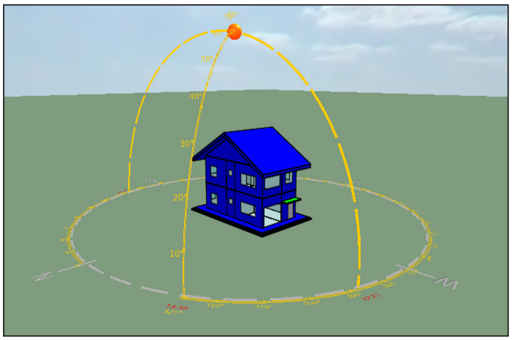


Figure 10. The tested house in IES-VE software

RESULTS AND DISCUSSION

A comparison of the operative temperature of the simulated cases has been made by applying full-day ventilation (all windows and internal doors were opened for 24 hours) and no ventilation (all windows and doors were closed for 24 hours) to find the best strategy that can achieve thermal comfort for the tested house.

Shading Devices and Curtains

Adding Shading Devices with Full-Day Natural Ventilation. In this case, 1-meter depth shading devices have been added above all the windows of the house from outside to decrease the direct solar radiation that enters the house. Table 3 shows the average operative temperature of April for the simulated cases with full natural ventilation. Figure 11 shows the hourly operative temperature—an average for April, and patterns of the simulated cases with full-day ventilation when shading devices have been added.

By referring to Table 3 and Figure 11, there is a slight reduction in the mean, maximum and minimum operative temperature when adding shading devices and applying 24 hours natural ventilation for all three rooms. The highest reduction happened in the maximum operative temperature of Room 1 (0.45 °C).

As full-day natural ventilation was applied for this case, the outdoor air can enter the rooms and affect the indoor environment. Subsequently, no ventilation strategy was applied by closing all the windows and doors for the same case to remove the effect of outdoor air.

Adding Shading Devices and Curtains with No Ventilation. In the previous case, adding closed curtains was not applicable because the windows were opened 24 hours for ventilation purposes, while it could be applied with no ventilation strategy when all the windows and internal doors were closed. Table 4 shows the average operative temperature of April for the simulated cases with no ventilation. Figure 12 shows the average hourly operative temperature for April of the simulated cases with no ventilation.

By referring to Table 4 and Figure 12, a good reduction happened in the mean, maximum and minimum operative temperature when adding shading devices and closing the curtains. At the same time, there was no ventilation in the three rooms. Therefore, the highest reduction was gotten for the maximum operative temperature of Room 1 (the reduction was 2.38 °C), followed by the maximum operative temperature of Room 3 (the reduction was 2.12 °C).

These results can cope with the results of several studies that have been conducted to examine the effect of blocking solar radiation when a shading device was positioned above one of the windows of the building to block sun gain in summer (Taleb, 2014). The results showed that shading had a significant effect on temperature reduction.

In the study of Kim et al. (2015), results showed a 35.1% reduction in the total cooling load caused only by blocking solar radiation due to the external shading added to the tested building.

Moreover, Kim et al. (2017) and Kamal (2010) mentioned that minimising solar radiation by adding external horizontal shading devices for the windows could cool the building effectively and decrease the energy consumption needed.

Regarding closing the curtains, Huang and Kang (2021) concluded that an improvement was achieved in an indoor thermal environment when closing curtains by reducing overheating time to an average of 62.2%. Thus, the comfort time was increased accordingly.

Using Timber and Clay Roof Tiles

The reference case's external and internal walls and flooring construction material have been changed to timber boards (20mm thickness) for the tested house. In contrast, other original conditions of the reference case remained. Then, the concrete tiles of the roof were changed to clay roof tiles. Both simulations were done with full-day natural ventilation and no ventilation separately.

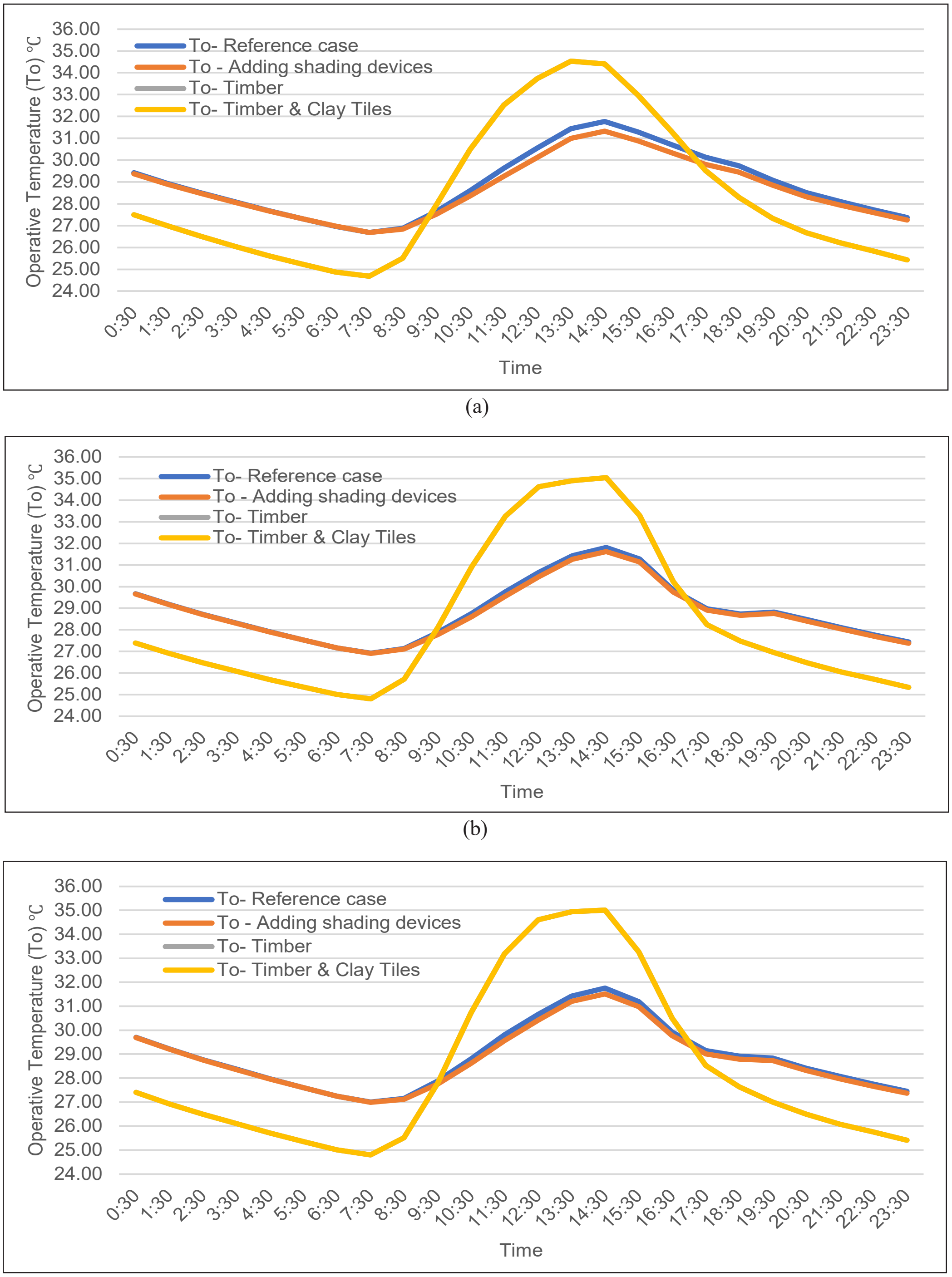
Using Timber and Clay Roof Tiles with Full-Day Ventilation. Table 3 also shows the average operative temperature for April for the simulated cases with full-day ventilation. Figure 11 shows the average hourly operative temperature of April of the simulated cases with full-day ventilation when using timber and clay roof tiles.

By referring to Table 3 and Figure 11, it can be noticed that using timber only or combining it with clay roof tiles (represented by the grey line in Figure 11, however, it is hidden under the yellow line because they both have similar values) can decrease the indoor operative temperature during night-time and early morning when there is no solar insolation. A good reduction happened in the minimum operative temperature (2.01, 2.11, & 2.20 °C) for Room 1, Room 2 and Room 3 when using only timber or timber and clay roof tiles in the case of full-day ventilation in the three rooms during night-time and early morning. However, using these materials was not significant during the daytime in all three

Table 3

Adding shading devices, using timber, and using clay roof tiles with full-day ventilation

Thermal variables	Statistics	Reference case	Adding Shading Devices	Using Timber	Using Timber & Clay roof tiles
		Room 1			
Operative temperature (°C)	Mean	28.87	28.68	28.34	28.34
	Maximum	31.78	31.33	34.54	34.54
	Minimum	26.69	26.59	24.68	24.68
		Room 2			
Operative temperature (°C)	Mean	28.84	28.77	28.33	28.33
	Maximum	31.81	31.63	35.04	35.04
	Minimum	26.92	26.91	24.81	24.81
		Room 3			
Operative temperature (°C)	Mean	28.88	28.77	28.34	28.34
	Maximum	31.76	31.51	35.01	35.01
	Minimum	27.00	26.90	24.80	24.80



(a)

(b)

(c)

Figure 11. The hourly operative temperature patterns of the simulated cases with full day ventilation strategy when adding shading devices, using timber, and using clay roof tiles: (a) Room 1; (b) Room 2; (c) Room 3

rooms. On the contrary, there was a high increment in the maximum operative temperature (2.76, 3.23 and 3.25 °C) for Room 1, Room 2, and Room 3. These results can cope with the results of Adekunle and Nikolopoulou's (2016) study, who stated that, while the timber is increasingly being utilised in building construction due to its environmental aspects and capacity to shorten total construction time when compared to conventional materials, the lack of thermal mass and low U-values can be a critical factor in increased overheating.

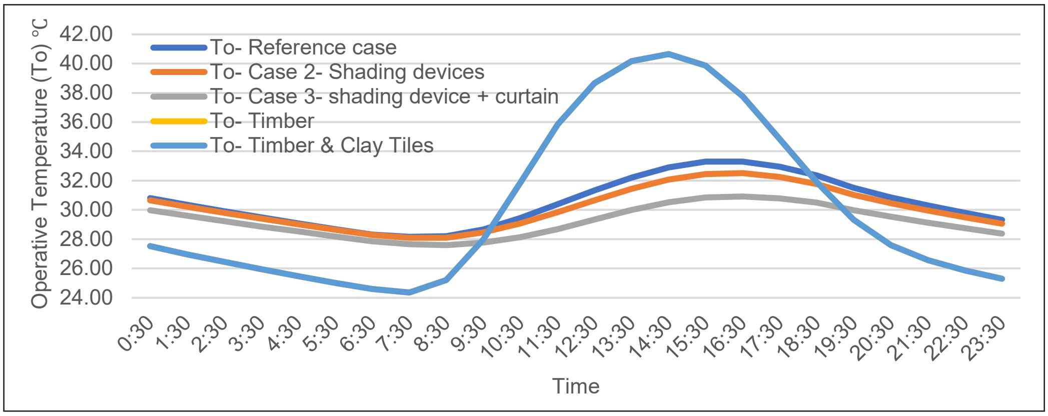
Therefore, using timber only or combining it with clay roof tiles is not significant for the tested house when full-day ventilation is used. Moreover, it is noticed that there was no difference in the mean, maximum and minimum operative temperature between using timber only or combining it with clay tiles for the three rooms due to the approximate u-value of clay roof tiles and concrete roof tiles for the same thickness (Table 2) as previously proved by Oleiwi (2020).

Using Timber and Clay Roof Tiles with No Ventilation. Table 4 also shows the average operative temperature of April for the simulated cases with no ventilation. Figure 12 shows the average hourly operative temperature for April of the simulated cases with no ventilation.

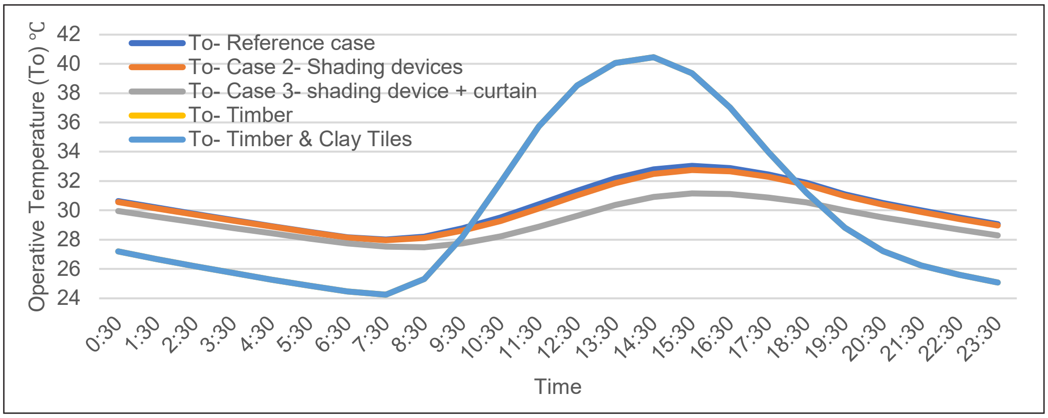
When there is no ventilation, the situation worsens during the daytime because the hot air is trapped inside the rooms. By referring to Table 4 and Figure 12, it can be noticed that a high increment happens when using timber only or combining it with clay roof tiles in the maximum operative temperature (7.35, 7.42 & 7.62 °C) for Room 1, Room 2, and Room 3. However, the situation was different during the night-time. There were decrements in the minimum operative temperature (3.80, 3.77 & 3.89 °C) for Room 1, Room 2 and Room 3.

Table 4
Adding shading devices and curtains, using timber, and using clay roof tiles with no ventilation

Thermal variables	Statistics	Reference case	Shading Devices	Shading Devices + Curtains	Using Timber	Using Timber & Clay Roof Tiles
Room 1						
Operative temperature (°C)	Mean	30.48	30.11	29.20	30.24	30.24
	Maximum	33.30	32.51	30.92	40.65	40.65
	Minimum	28.15	28.10	27.59	24.35	24.35
Room 2						
Operative temperature (°C)	Mean	30.30	30.16	29.24	29.97	29.97
	Maximum	33.03	32.76	31.15	40.45	40.45
	Minimum	28.01	27.96	27.49	24.24	24.24
Room 3						
Operative temperature (°C)	Mean	30.35	30.15	29.16	30.00	30.00
	Maximum	32.98	32.57	30.86	40.60	40.60
	Minimum	28.14	28.09	27.55	24.25	24.25



(a)



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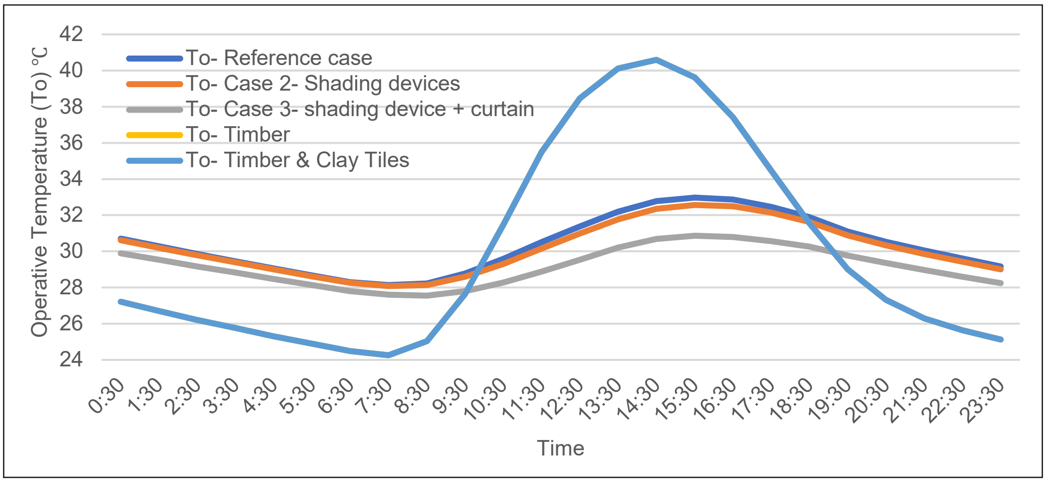


(c)

Figure 12. The hourly operative temperature patterns of the simulated cases with no ventilation strategy when adding shading devices, adding closed curtains, using timber, and using clay roof tiles: (a) Room 1; (b) Room 2; (c) Room 3

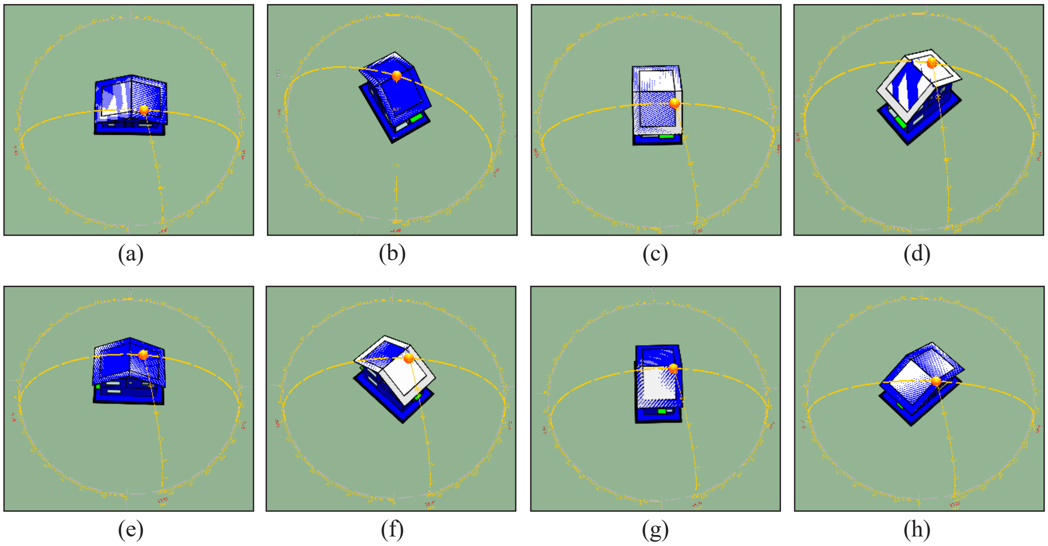
Other studies showed similar results. For example, the study by Dong et al. (2019) proved that using a type of timber (cross-laminated timber (CLT)) in office buildings in China had a significant effect on decreasing energy consumption of heating in the Cold Region and Severe Cold Regions of China; however, the CLT buildings consumed more energy for cooling in the summer. Thus, this type of construction is not suitable for hot regions. In addition, Khavari et al. (2016) concluded that cross-laminated timber generally provides a significant improvement in heating energy efficiency as a heavy and air-tight envelope, but its energy performance efficiency can be affected by weather, building size, internal loading, and HVAC control.

In the North European climate, the results of Kildsgaard et al. (2013) showed that airtight, low-energy apartment buildings could be successfully built with prefabricated timber elements in a cold climate.

Changing the Orientation of the House

Seven orientations for the angles 45, 90, 135, 180, 225, 270, and 315 degrees have been examined and compared with the reference case, which is considered as zero angle orientation. In contrast, other original conditions of the reference case remained. Figure 13 shows the eight orientations of the tested house. The simulations were done with full-day natural ventilation and no ventilation separately.

Changing the Orientation of the House with Full-Day Ventilation. Table 5 shows the average operative temperature for April for the simulated cases with full-day ventilation.

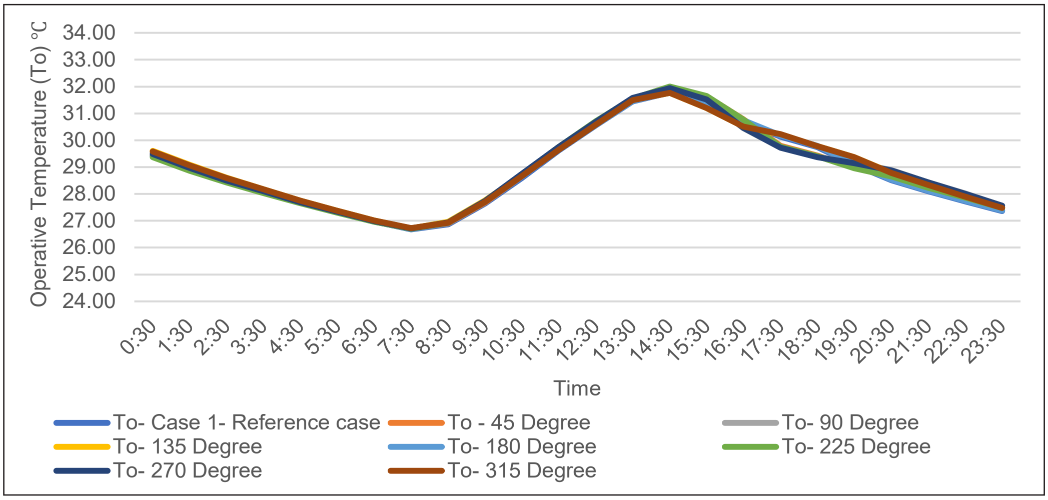

(a) (b) (c) (d)

(e) (f) (g) (h)

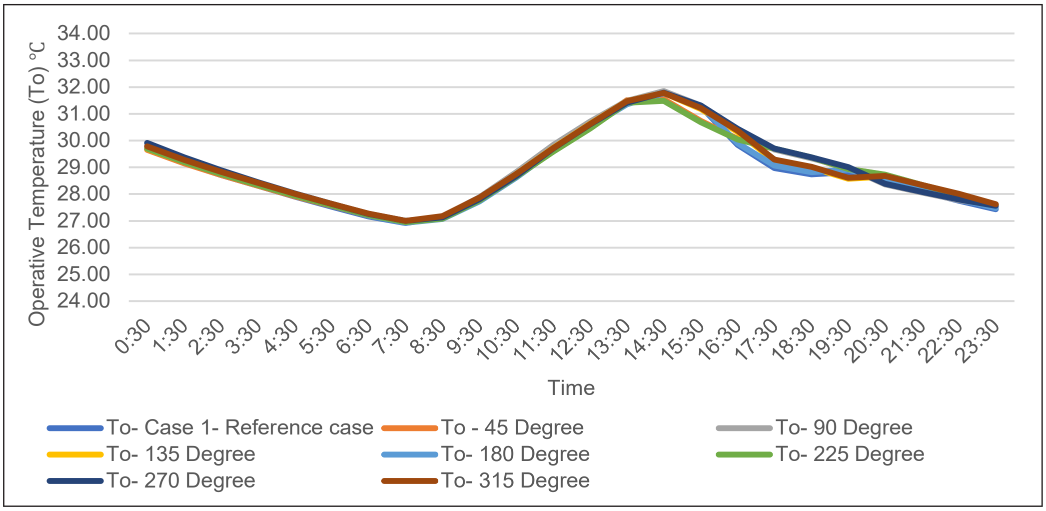
Figure 13. The eight orientations of the tested house: (a) Zero degree; (b) 45 degree; (c) 90 degree; (d) 135 degree; (e) 180 degree; (f) 225 degree; (g) 270 degree; (f) 315 degree

Figure 14 shows the average hourly operative temperature for April of the simulated cases with full-day ventilation.

By referring to Table 5 and Figure 14, it can be noticed that there was no significant difference for all the seven cases compared with the reference case when the full-day ventilation strategy was applied. However, the lowest two directions are 0 and 180 degrees. The main reason for no significant difference could be because the house has big windows from all four sides; thus, it was exposed to solar radiation from all four sides even when the direction of the facades was changed. The other reasons could be that the house is too small with the distance between walls is close to each other, the pure rectangular shape of

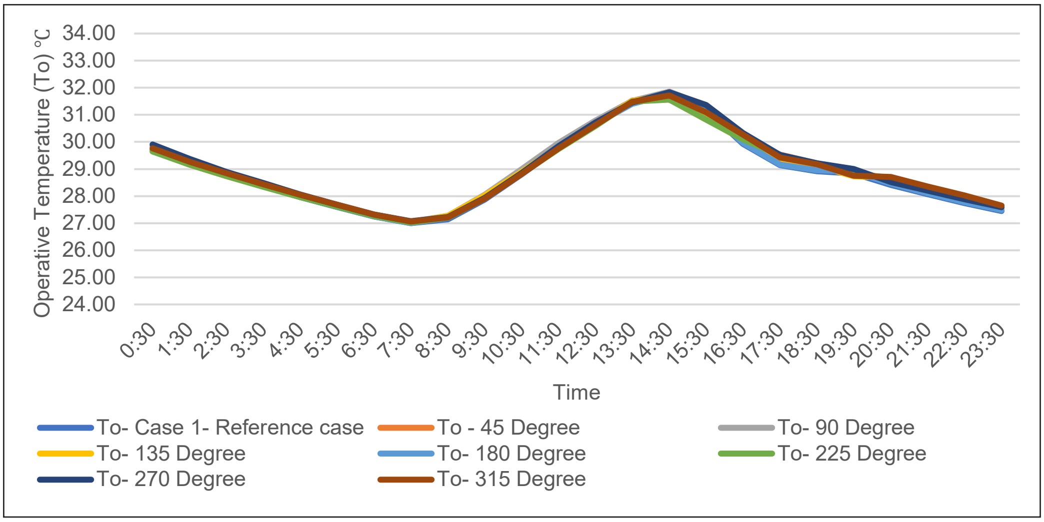


(a)



(b)

Figure 14. The hourly operative temperature patterns of the simulated cases with full day ventilation strategy of the eight orientations: (a) Room 1; (b) Room 2

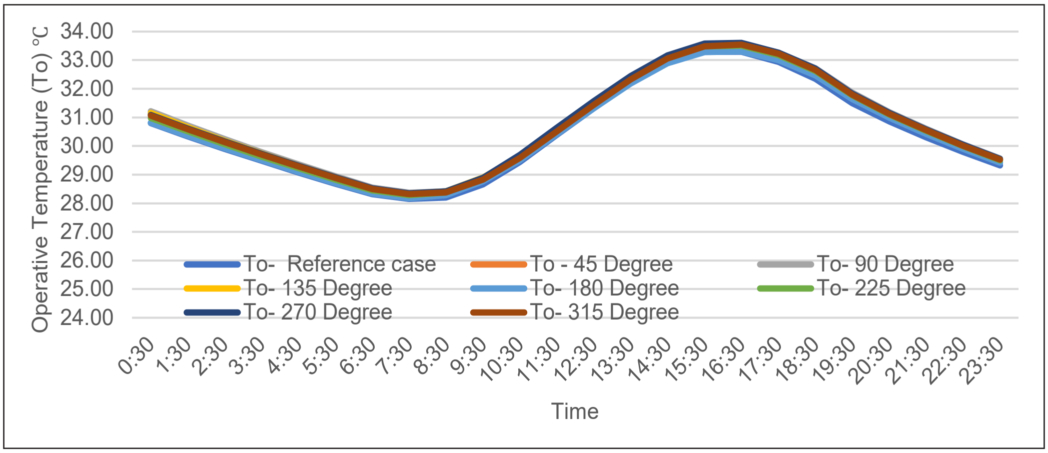


(c)

Figure 14 (continue). The hourly operative temperature patterns of the simulated cases with full day ventilation strategy of the eight orientations: (c) Room 3

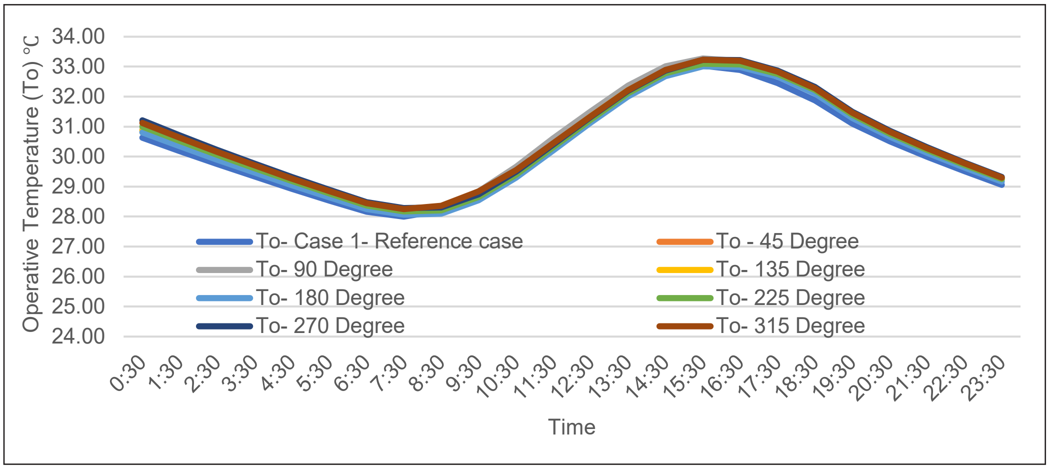
the building (close to being square) and the façade of the building is almost clean without significant protruding elements, which could protect the façade from the sun heat.

Changing the Orientation of the House with No Ventilation. Table 6 shows the average operative temperature of the month of April for the simulated cases with no ventilation. Figure 15 shows the average hourly operative temperature for April of the simulated cases with no ventilation.

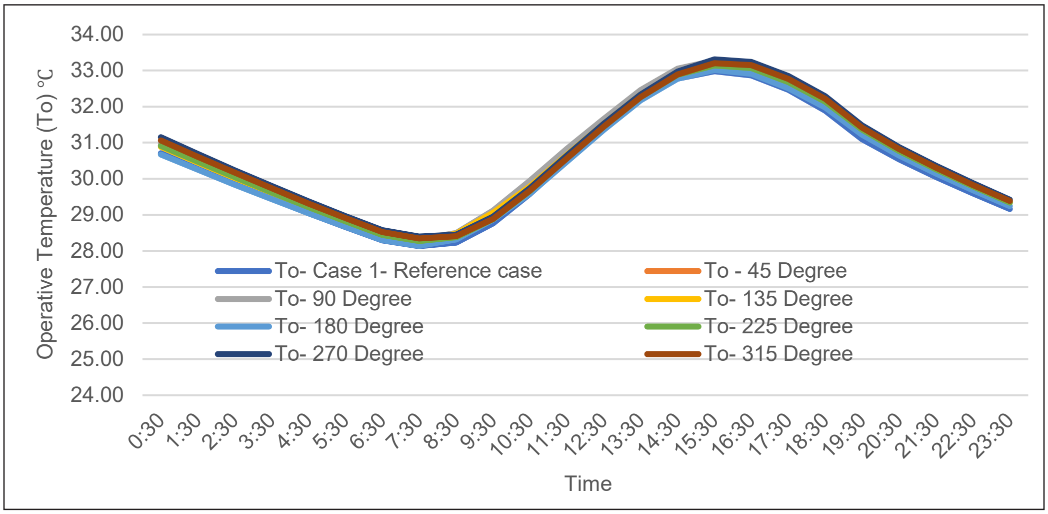


(a)

Figure 15. The hourly operative temperature patterns of the simulated cases with no ventilation strategy of the eight orientations: (a) Room 1



(b)



(c)

Figure 15 (continue). The hourly operative temperature patterns of the simulated cases with no ventilation strategy of the eight orientations: (b) Room 2; (c) Room 3

By referring to Table 6 and Figure 15, it can be noticed that there was no significant difference for all the seven cases compared with the reference case when no ventilation was applied. The reason for that could be the same as when the full-day ventilation strategy was applied.

In Malaysia, it is recommended to expose glazing to the North and South and avoid exposure to the East and West (Tang & Chin, 2013). However, the same study showed that the most significant factor for lowering building energy consumption in a building is decreasing the glazing area. Therefore, removing the windows from two opposite sides is recommended, testing different orientations.

Table 5

Changing the orientation of the tested house with full-day ventilation

Thermal variables	**Statistics**	**Reference case**	**45 Degree**	**90 Degree**	**135 Degree**	**180 Degree**	**225 Degree**	**270 Degree**	**315 Degree**
				Room 1					
Operative temperature (°C)	Mean	28.87	28.89	28.92	28.95	28.89	28.90	28.93	28.95
	Maximum	31.78	31.96	31.89	31.76	31.79	32.01	31.94	31.77
	Minimum	26.69	26.71	26.72	26.72	26.69	26.71	26.72	26.73
				Room 2					
Operative temperature (°C)	Mean	28.84	28.91	28.97	28.91	28.85	28.90	28.97	28.95
	Maximum	31.81	31.55	31.85	31.78	31.77	31.48	31.79	31.78
	Minimum	26.92	26.95	26.96	26.96	26.94	26.96	27.00	27.00
				Room 3					
Operative temperature (°C)	Mean	28.88	28.95	29.01	28.97	28.89	28.92	29.01	28.97
	Maximum	31.76	31.61	31.86	31.73	31.76	31.57	31.84	31.71
	Minimum	27.00	27.03	27.06	27.05	27.00	27.03	27.07	27.06

Table 6

Changing the orientation of the tested house with no ventilation

Thermal variables	**Statistics**	**Reference case**	**45 Degree**	**90 Degree**	**135 Degree**	**180 Degree**	**225 Degree**	**270 Degree**	**315 Degree**
				Room 1					
Operative temperature (°C)	Mean	30.48	30.48	30.48	30.48	30.48	30.48	30.48	30.48
	Maximum	33.30	33.30	33.30	33.30	33.30	33.30	33.30	33.30
	Minimum	28.15	28.15	28.15	28.15	28.15	28.15	28.15	28.15
				Room 2					
Operative temperature (°C)	Mean	30.30	30.47	30.52	30.45	30.34	30.45	30.57	30.55
	Maximum	33.03	33.23	33.28	33.16	33.01	33.10	33.23	33.23
	Minimum	28.01	28.13	28.17	28.14	28.06	28.17	28.28	28.26
				Room 3					
Operative temperature (°C)	Mean	30.4	30.57	30.63	30.54	30.39	30.52	30.65	30.58
	Maximum	33.0	33.21	33.27	33.17	33.02	33.14	33.31	33.20
	Minimum	28.1	28.28	28.33	28.28	28.14	28.27	28.40	28.35

CONCLUSION

In this study, three main passive cooling strategies were applied to the tested house using IES-VE 2019 building simulation software to find the best thermal comfort strategy that can be achieved for a double-storey house in the tropical climate of Malaysia. The first passive cooling strategy was decreasing the direct solar radiation that enters the house from the windows, which was achieved by adding shading devices over the windows and closing the curtains inside the rooms. The second passive cooling strategy examined different construction materials, timber for walls and floors and clay tiles for the roof. The third passive cooling strategy was changing the orientation of the house by examining seven orientations and comparing them with reference cases. All these simulations were tested for full-day natural ventilation and without any ventilation. The thermal comfort of these strategies was defined based on the operative temperature.

Under full-day natural ventilation, the study revealed that adding external shading devices to the windows could decrease the operative temperature inside the three rooms. Moreover, using timber for walls or combining it with clay tiles for the roof was not effective during the daytime; however, the indoor operative temperature was decreased during night-time and early morning when there is no solar insolation. Changing the orientation of the building did not give any significant difference in the indoor operative temperature compared with the reference case when full-day ventilation was applied.

Under conditions without ventilation, the study revealed that adding external shading devices and closing the curtains inside the rooms had the lowest operative temperature compared to other examined strategies. On the other hand, using timber for walls or combining it with clay tiles for the roof was ineffective during the daytime. At the same time, it could decrease the indoor operative temperature during night-time and early morning. Similar to full-day ventilation, no significant difference was noticed in the indoor operative temperature when changing the orientation of the building when all the openings were closed.

Comparing full-day natural ventilation and without any ventilation, the study reveals that protecting the windows from solar radiation by adding external shading devices (when full-day ventilation was applied) and combining them with closing the curtains inside the rooms (when no ventilation was applied) had the lowest indoor operative temperature compared to other examined strategies. The results also showed that using timber for walls and clay tiles for the roof was ineffective during the daytime.

In addition, changing the orientation of the house was not a good suggestion in the case of this building, as no significant decrement happened in the operative temperature inside the three rooms of the house. Nevertheless, it is recommended to examine changing the orientation of the house while removing the windows from the long facades of the house and using other shading strategies, such as using vertical green walls. A further study is required to investigate the effect of orientation on indoor thermal comfort while avoiding exposure to all the fourth directions.

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