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EFFECTS OF SHADING DESIGN OPTIONS ON THERMAL AND DAYLIGHTING PERFORMANCE OF A MODULAR HOUSE IN MELBOURNE

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Abstract: Prefabrication of houses is a growing industry in Australia. Although prefabrication does not negatively affect the building quality, the potential to provide acceptable indoor environment quality with high energy efficiency is still a topic of argument. Effective passive design strategies are necessary to achieve low-energy buildings with satisfactory indoor environment quality. The building envelope parameters such as materials, openings and shadings highly affect the heat transfer, air exchange and light transmission between outside and indoor environment. Shading, one of the passive envelope design strategies, can reduce cooling energy while improving the indoor thermal comfort. However, the effects on daylighting and thermal performance depend on the climate conditions, and the size, location and orientation of the shading device. The performance benchmarks of prefabricated houses have not been well documented in the literature. The aim of this paper is to investigate the effects of shading design options on thermal and daylighting performance of a typical modular house in Melbourne. EnergyPlus and Radiant simulation engines have been employed in this study. By quantifying the performance, the appropriate shading design for the typical modular house in Melbourne could be identified.

Keywords: Envelope design; Shading, Thermal performance; Daylighting; Prefabricated houses;

1. Introduction

With the growing population and uncoordinated developments of the cities, sustainability and liveability of built environment have become a critical focus area in most countries. More and more sectors throughout the world became eager to modify their process to prioritise considerations for reducing greenhouse gas (GHG) emissions and increasing energy efficiency. Buildings are responsible for a large amount of energy consumption (about 40% of world's total energy consumption) and GHG emissions [1].

For instance in Europe, buildings account for 40% of the energy consumption and 36% of the GHG emissions [2]. Energy consumption of residential and commercial buildings in the US was about 27% of total consumption in 2016, while residential buildings were responsible of 6.7% [3]. In Australia 14% of total energy consumption is associated with commercial and residential buildings, residential buildings are responsible for 7.7% [4].

People spend most of their times indoors. Therefore, the comfort levels and satisfaction of indoor environment can easily affect the quality of their daily life. Indoor environmental quality (IEQ) is referred to as the factors that satisfy the occupants' comfort levels and does not increase the risk or severity of discomfort or illness [5]. Factors influencing IEQ are: thermal comfort, visual comfort, acoustic comfort, hygienic comfort and olfactory comfort [6]. Studies investigating the importance of IEQ parameters showed that occupants thermal comfort and indoor air quality are on the top of the importance list [7], [8].

Considering the necessity of affordable, liveable, resilient and sustainable housing, prefabrication offers benefits to construction industry with reductions in time, cost and waste. Furthermore, due to standardisation of materials and quality control, prefabricated houses are claimed to have better overall quality and environmental performance. Modular construction is one of the most advanced off-site manufacturing methods which complete up to 70% of construction in the factory. The pre manufactured components and modules are transported to the building site [9].

Although prefabrication and off-site manufacturing does not negatively affect the building quality, the potential to provide acceptable indoor environment quality with high energy efficiency is still a topic of argument. Considering that up to 70% of buildings' energy consumption is associated with the operational phase [10], It is important to reduce the operational energy of the buildings by improving thermal performance of the buildings.

Thermal comfort is defined as the situation of body in which the occupant will not desire neither warmer nor cooler environment [11]. Sunlight affects the buildings in terms of thermal and visual comfort. Solar radiation can enter through the glazed surfaces of the building providing illumination, while being absorbed by interior surfaces of the building causing a heating effect. It can also be absorbed by exterior surfaces of the building, which will be partly conducted to the indoor air [11], [12]. Factors such as window type, size and orientation, building envelope, and shading can affect the amount of heat and illumination inside the buildings due to the solar radiation outside [12].

Although The effects of passive strategies and solar design of thermal and visual comfort have been investigated by several researchers [13-16], the thermal and visual comfort levels in prefabricated/modular houses have not been well documented in the literature. It is necessary to investigate the current baseline performance of these houses. By doing so the future houses to be constructed can be better.

Using shading devices is one of the strategies to optimise the amount of solar heat gain in the buildings. Depending on the building location and window orientation various types of shading devices can be applied to prevent the excessive heat gain and reduce the cooling load in summer and harvest the solar energy in winter. Vertical, horizontal and egg-crate type devices are the most prevalent shading orientations [12].

This paper investigates the effects of shading devices on the cooling and heating loads and daylighting performance of a typical modular house in Melbourne, Australia. This is a part of baseline thermal performance evaluation of prefabricated modular houses. The materials and systems investigated in this paper are currently available in the Australian market. Building energy simulation and daylighting analysis has been carried out on the building with different shading options.

2. Methods

2.1. Base building

The building which is used in this study is a single story modular house called "Nano-flat". This house is a typical example of prevalent modular houses currently available in Australia. The house has two bedrooms, two bathrooms and a living room, with a total floor area of about 52 m^2 (Figure 1). The detailed specifications of the building components and the properties of materials are presented in Table 1.

Figure1: Floor plan of Nano-flat house

2.2. Simulation Engines

The thermal performance predictions of the typical house selected was carried out using EnergyPlus 8.6.0 simulation engine. The 3D models of the buildings were generated using "OpenStudio" Sketchup plug-in. OpenStudio also uses Radiance, advanced daylight analysis software. All required inputs and parameters of the house were defined in OpenStudio. Additional features such as illuminance map and daylighting controls were added to the model to investigate the daylighting performance. In this study the main aim of the simulations is to investigate thermal and daylighting performances with special focus on the shading designs which may be implemented. In this respect, all other parameters that affecting the cooling and heating loads, and daylighting are considered fixed. They include location, window orientations, building envelope and thermostat settings. Furthermore, internal heat loads related to occupancy and equipment inside the building were not considered in the model. It should be noted that the heating and cooling loads of the same building can differ because of the usage schedule and internal heat gains. However, since in this study only the changes in heating/cooling loads as the effects of shading options are being investigated, this fact does not affect the results.

EnergyPlus website provides weather data for Melbourne which is based on a representative metrological year (RMY) developed by "Australia Greenhouse Office" [17]. To acquire the data set suitable for prediction of long term thermal performance "Meteonorm" software tool was applied. It provides worldwide weather data in various formats based on the observations from 8325 weather stations all around the world [18]. Data source used by this software is World Meteorological Organization (WMO).

Table 1: The properties of selected materials of each components of the building

Component	Material	Thickness (mm)	Conductivity	Density (kg m^{-3})	Specific heat (J kg^{-1}.K^{-1})
Exterior Wall	*Fibercement	10	0.25	1360	1000
	*FAUX Timber	10	0.15	608	1630
	OSB board	20	0.13	640	840
	Insulation	90	0.043	91	837
	OSB board	20	0.13	640	840
	Plasterboard	10	0.19	1300	840
Interior Wall	Plasterboard	10	0.19	1300	840
	Air space	90	-	-	-
	Plasterboard	10	0.19	1300	840
Floor	Lightweight concrete	70	0.53	1280	840
	Air space	150	-	-	-
	OSB Board	20	0.13	640	840
	Insulation	170	0.049	265	836
	OSB board	20	0.13	640	840
	**Ceramic tiles	15	1.3	2300	840
	**Carpet	15	0.06	288	1380
	**Wood	15	0.15	608	1630
Roof	Stainless steel	1.5	45	7680	418
	EPS insulation	200	0.038	15	1130
	Stainless steel	1.5	45	7680	418
Door	Wood	25	0.15	608	1630

*Two types of materials are used in building façade finishing. On some surfaces, FAUX Timber cladding is used while other surfaces use fibrecement cladding.

**For bathroom ceramic tiles; for living room timber flooring and for bedrooms carpet flooring are used.

For all simulations 'Ideal Air Load' option was selected in EnergyPlus. The conditioned zones are the living room and the two bedrooms. According to [19] the heating degree days are highest during the period from 1 May to 31 October; whist the cooling degree days are higher from 1 December to 28 February. In this study, these durations were set as heating and cooling seasons. The space conditioning system was assumed to be switch off during other seasons. The thermostat set point for heating was 21°C during daytime (6 am – 10 pm) and during nighttime (10 pm – 6 am) the setback was 18°C. The thermostat set point for cooling was 24°C. The assumed air infiltration rate was 1 ACH. The windows are 3 mm thick single glazing having U-factor of 6.24 $Wm^{-2}K^{-1}$ and solar heat gain coefficient (SHGC) of 0.252.

2.3. Investigated Shading Design Options

External shading devices are regarded as the most efficient solar controls. These devices can be defined according to the position of the sun relative to the window orientation. Solar geometry is used to determine the optimum shading size and orientation. The building location plays a crucial role when it comes to the solar control. The solar altitude angle (γ) and solar azimuth angle (α) as well as vertical shadow angle (ε) changes depending on the latitude and the orientation of the shading device throughout the year (Figure 2a).

Fixed shading devices reduce the amount of solar radiation entering the building. Thus, they can increase the heating load during winter. However, since the position of the sun relative to the window changes throughout the year, it is possible to adjust the dimensions and shape of the shading device to provide shadow during summer while letting the sun in during winter (Figure 2b). Adjustable shading devices are other possible options which are more expensive but more effective since they provide the variable dimensions.

Sun path diagrams are applied to determine solar angles to design the effective shading devices. The Climate Consultant 6.0 software is a user-friendly tool that facilitates the design of shading devices by providing sun path diagrams [20]. It also enables the users to visualise the effects of vertical shadow angle and to identify the optimum shading size. In this study, Climate Consultant was used to determine the dimension of horizontal devices on the north facing windows. The software displays hot, cold and comfortable hours for the whole year on the sun path diagrams. The comfort levels selected in this study are according to ASHRAE Standard 55.

The first step in sizing the shading devices is to determine the shading type. Nano-flat house has windows only on northern and southern walls. Considering the latitude of Melbourne, horizontal shading devices are required only on northern windows. The horizontal shading size depends on the vertical shadow angle, ε (see Figure 2a) and the window height. By using Climate Consultant tool, the vertical shadow angle was adjusted to cover the specified hot days of the year during the summer. After acquiring the angle and the window height the overhang length of the shading device can be determined. The glass door (height = 2 m) and three windows (height = 1.9 m) on the northern wall were considered in shading analysis.

The shading options investigated in this study are for various vertical shadow angles (ε). By choosing the vertical shadow angle of 67° most of the hot days during December and January, the windows would be shaded

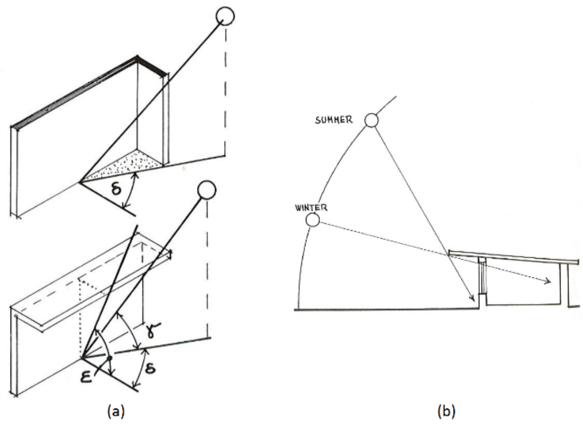


Figure2: (a) Important angles in determining the shading devices, (b) Summer/winter shading [12]

. Another option suggested by Climate Consultant is the vertical shadow angle of 63° which covers most summer days but also provides shading during November. In this study, other vertical shadow angles (50°, 60°, 70° and 80°) were also investigated. Based on the vertical shadow angle and the height, the overhang length was estimated for each angle. To investigate the effect of shading on thermal and daylighting performance of the Nano-flat house, all options have been modelled and simulated by using EnergyPlus and Radiance simulation engines. Furthermore, to carry out a valid comparison a base building without shading was modelled. Figure 3 shows an example of the modelled building with the horizontal shading device. The window shape and sizes are visible in the figure. Table 2 shows the overhang lengths of the horizontal shading with respect to the vertical shadow angle selected.

Table 2: The overhang length of the horizontal shading vs the vertical shadow angle.

Vertical shadow angle, ε (Degree)	Overhang length of shading (m)
90	0.00
80	0.33
70	0.70
67	0.81
63	0.97
60	1.09
50	1.59

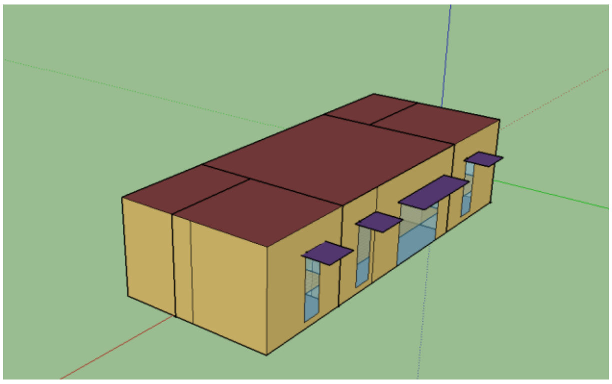


Figure 3: The modelled building with shading devices.

3. Results and Discussion

The results of simulations including thermal performance and daylighting performance are presented in this section.

3.1 Thermal Performance

For different shading options, Figure 4 and 5 show the changes in annual cooling and heating loads per unit floor area respectively. Vertical shadow angle indicates the overhang length of the shading device (see Table 2). Cooling load decreases with a decrease in the vertical shadow angle (increasing the overhang length of shading, see Figure 4). The cooling load reaches minimum when the vertical shadow angle is 67° and it remains relatively constant by further reduction of the angle. As discussed previously by choosing 67° the shading device provides shadow on the windows during hot days in December and January (generally the hottest months in Melbourne). Providing shading with 67°, the cooling load decreases by 12.5% compared to the base building without shading.

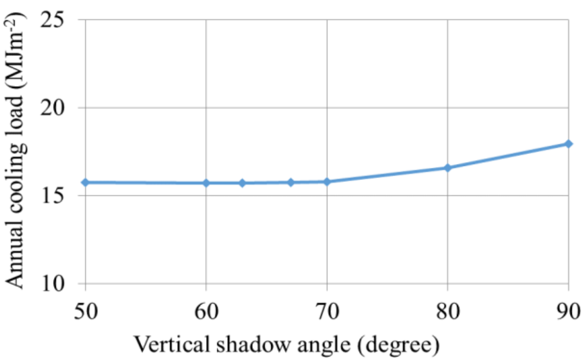


Figure 4: Annual cooling load

It is apparent from Figure 5 that the annual heating load consistently increases by reducing the vertical shadow angle. This increased heating load is a result of preventing solar ration to enter the building during winter. Although the rate of increase in heating load is smaller than the rate of decrease in cooling load, (by providing shading with 67°, the heating load increases by 3.67% compared to base building while the reduction rate of cooling load is 12.5%), since for the climate of Melbourne the annual amount of heating load is significantly higher than cooling load, the total annual electricity consumption increases by providing any type of shading on the building.

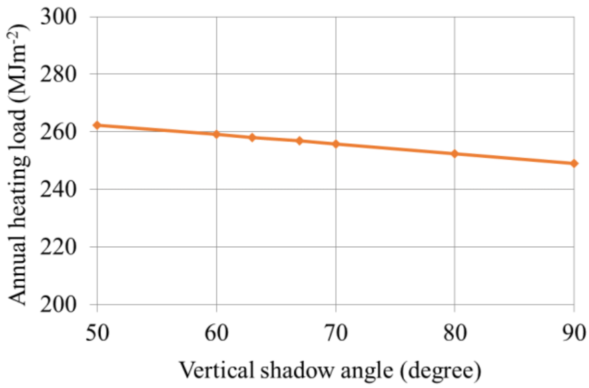


Figure 5: Annual heating load

Figure 6 shows the annual electricity consumption for heating and cooling of the investigated shading options. For estimating annual electricity consumption, the peak cooling and heating loads were extracted from the results. By using Australian energy star rated equipment list for cooling and heating. The equipment with sufficient capacity for peak demand was selected and its coefficient of performance (COP) was calculated by using the specified configurations [21]. It is evident from Figure 4 and 5 that the electricity consumption for heating is significantly higher than that of cooling.

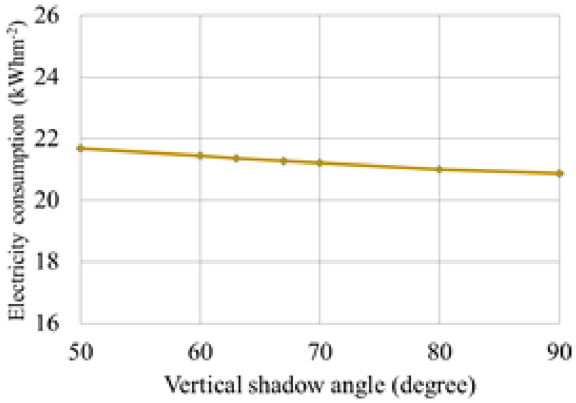


Figure 6: Annual electricity consumption

3.2 Daylighting performance

The results of daylighting analysis are presented in this section. The hourly illuminance maps of the building for the whole year are available in the result file. However in this paper only the summer and winter design day performance are presented. For Melbourne the summer design day is February 21st and the winter design day is July 21st. By considering standard illuminance requirements, living rooms should have general lighting level of 30-75 lux, while 150-300 lux is required for recreation purpose. For reading purpose the requirement is 300-750 lux (JIS Z 9110:2010). Australian standards require maintained illuminance of 160 lux for dining rooms and sitting areas while for moderately difficult task such as reading 400 lux is required (1680.1:2008; AS/NZS 1680.2.1:2008). Figure 7 shows the illuminance map of living room at 9:00 AM on July 21st while Figure 9 shows the daylighting performance in the living room at 8:00 AM on February 21st.

The colours shown on the illuminance map represent the illuminance levels of the room. The colour range can vary depended on the maximum and minimum illuminance level in the spaces. Red colour shows the maximum illuminance while the blue colour represents minimum illuminance. The maximum and minimum levels of each map are mentioned on the top of the map in Figure 7 and 8.

As it is apparent form Figure 8 the illuminance of the living room space ranges between 50 and 500 lux in the house without shading device. The maximum level of illuminance reduces to 350 lux for the building with ε=67° while it reaches 300 lux for the building with ε=50°.

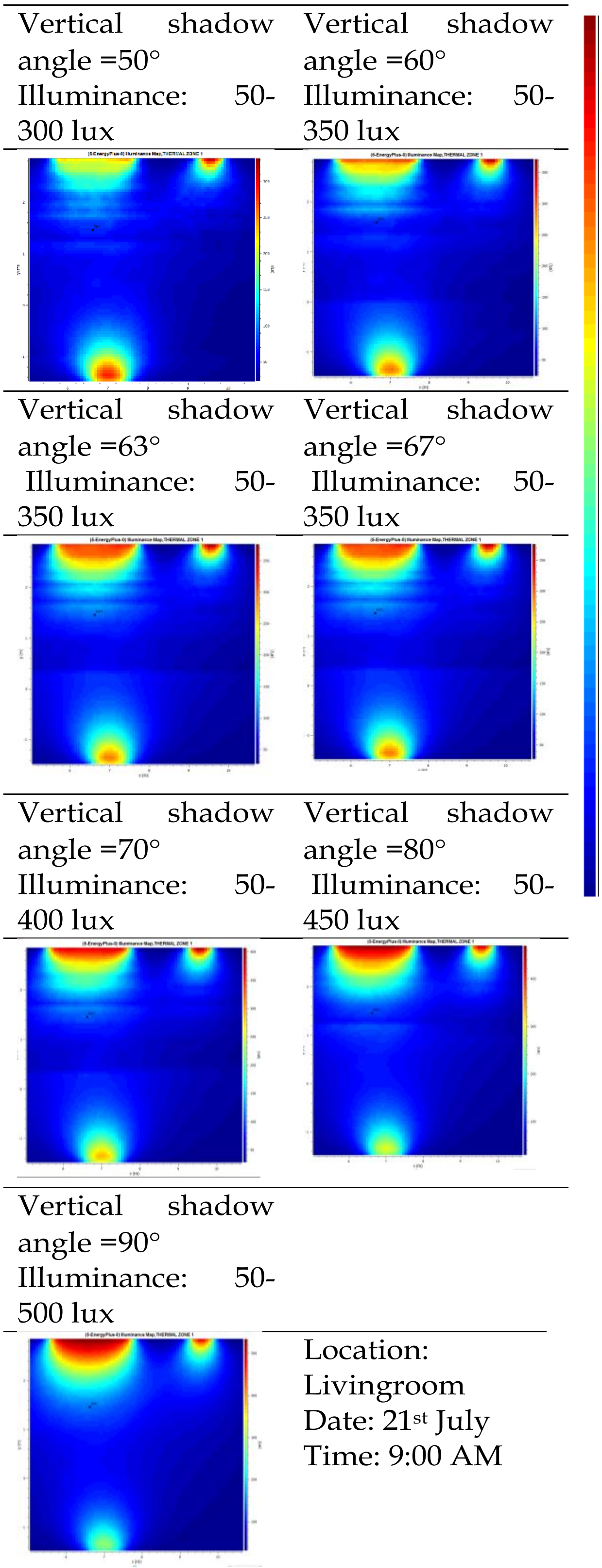


Figure 7: Illuminance maps of living room at 9:00 AM on July 21st.

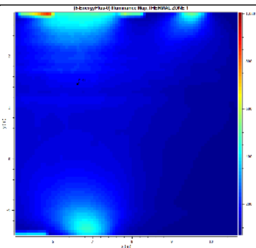
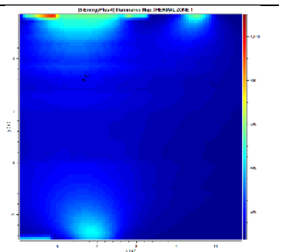
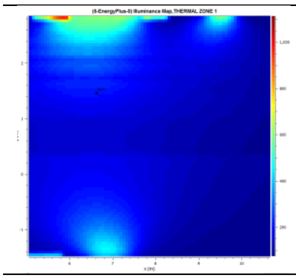
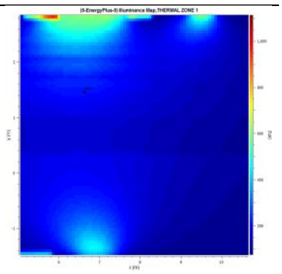
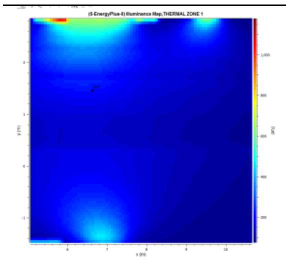
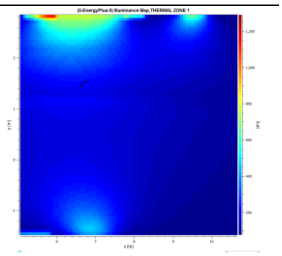
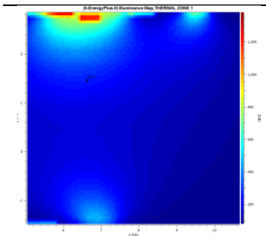
Vertical shadow angle =50° Illuminance: 100-1000 lux	Vertical shadow angle =60° Illuminance: 100-1000 lux
	
Vertical shadow angle =63° Illuminance: 100-1000 lux	Vertical shadow angle =67° Illuminance: 100-1000 lux
	
Vertical shadow angle =70° Illuminance: 100-1000 lux	Vertical shadow angle =80° Illuminance: 100-1000 lux
	
Vertical shadow angle =90° Illuminance: 100-1000 lux	
	Location: Livingroom Date: 21st February Time: 8:00 AM

Figure 8: Illuminance maps of living room at 8:00 AM on February 21st.

The blue areas in the middle of the illuminance maps illustrate the illuminances about 100 lux in ε=50°, 60° while the illuminance in the middle of the house increase to 130 lux in the house with ε=67°. The illuminance at the same location for the house with no shade is 170 lux. The green areas are in the illuminance range of 200-250 lux in the house with shade and 300 lux in the house without shade. The dark areas in the corner indicate illuminance of 50 lux or less.

It can be said from Figure 8 that the illuminance of the living room space ranges from 200 to 1000 lux at 8:00 AM in a summer day for all the options. Most spaces of the building except the area near the windows are blue colour which indicates the illuminance between 200 and 300 lux. The dark areas in the corner have the illuminance about 100 lux. The areas near the window which is in green colour show the illuminance of 400-500 lux.

Figure 9 and 10 show the hourly illuminance in the centre of living room throughout the summer design day and the winter design day respectively, for three shading options. The options selected are: no shade (ε=90°), maximum shade (ε=50°) and optimal shade (ε=67°). It is apparent from these figures that the optimal shading device provides sufficient lighting in the living room in winter while moderating the excessive illuminance during the summer.

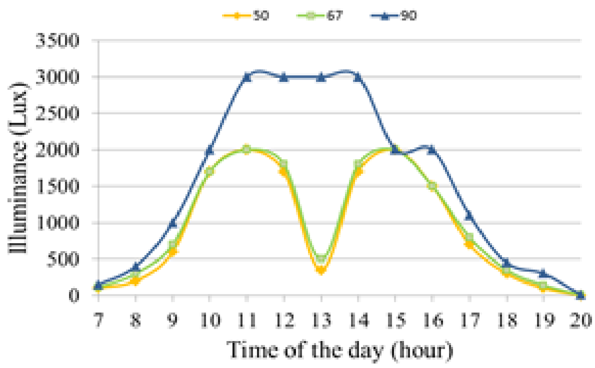


Figure 9: Hourly illuminance in centre of living room throughout the summer design day (February 21st), for no shade (ε=90°), maximum shade (ε=50°) and optimal shade (ε=67°).

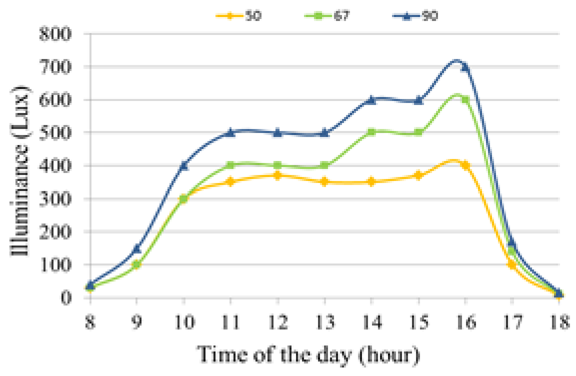


Figure 10: Hourly illuminance in centre of the living room throughout winter design day (July 21st), for no shade (ε=90°), maximum shade (ε=50°) and optimal shade (ε=67°).

4. Conclusions

In this paper the effects of shading design options of thermal and daylighting performance of a typical modular house in Melbourne was investigated. Melbourne has a heating dominant climate. The investigated building is a single family modular house with floor area of about 52 m². The house has a glass door and three 1.9 m high windows on the northern wall. This wall is the surface where the house gets the most solar radiation. Various overhang length were modelled and simulated by using computer software tools, to investigate the effects on the thermal and daylighting performance.

The comparisons of thermal performances and daylighting performances of the buildings with various shading overhang lengths reveal that the addition of larger horizontal shading devices can negatively affect the daylighting and thermal performance of the buildings by reducing illuminance levels and increasing heating loads. In this respect the selection of appropriate shading size is of great importance.

In terms of thermal performance, even though by adding shading devices the rate decrease in cooling load significantly (12.5%) is higher than the rate of increase in heating load (5.3%), due to significantly larger heating load for the climate of Melbourne, the total annual electricity demand for heating and cooling of the building increases. By considering the cooling load results for the investigated options, the building with an overhang length corresponding to ε=67°, is the appropriate size for shading since it produces maximum decrease in cooling load. The increase in the total electricity consumption increases by 1.9%. Considering the average price of electricity this would be about AU$ 6.11 annually.

In terms of daylighting performance, in overall the building receives sufficient daylighting due to the glass door and two large windows on the north wall. However by implementing longer overhang lengths of the horizontal shading, certain interior spaces of the house lack sufficient daylighting level recommended by the Australian standards. For instance, the winter design day the centre of the living room has illuminance of 500-700 lux without shade, while the same location has maximum illuminance of 200-300 lux with a shading ε=50°. This house requires additional artificial lighting for reading with ε=67° to provide sufficient illuminance. In similar circumstances, the selected optimal shading option provides maximum illuminance of 400-600 lux which is sufficient lighting for living room.

It may be concluded that addition of appropriate shading can be useful for reducing cooling load and control the daylighting illuminances and glare during the summer while maintaining sufficient illuminance during winter. The results show that, for Melbourne climate even though the heating load is significantly higher, an appropriate shading device can improve building visual comfort without significantly affecting the heating load.

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