A Baseline Study on Thermal Performance of Prefabricated Modular Buildings in Australia

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ABSTRACT

Prefabricated modular construction is one of building solutions that has positive effects on construction time and waste management. In general, thermal performance of the building envelope is an important parameter which dictates the operational energy consumption. There are some prefabricated modular buildings available in Australia. However, their thermal performance benchmarks have not been well documented in the literature. Innovative panel systems have been proposed to improve the cost competitiveness and to achieve better performance. It is essential to know the current performance so that newer panels can be proven to be better. This paper investigates the thermal performance of four prefabricated modular buildings currently available in the Australian market. The buildings were selected to represent single-family houses with different floor areas. A building energy performance simulation tool was used to predict the cooling and heating loads of each building. The findings based on the simulations are presented in this paper.

Keywords: *modular buildings, thermal performance, heating and cooling, energy simulation*

1. INTRODUCTION

Due to the increasing trend of energy usage and greenhouse gas (GHG) emissions, various sectors throughout the world give priority to reducing GHG emissions and increasing energy efficiency. Building sector accounts for almost one third of world's total energy consumption while it is the source for intense GHG emissions as well. For instance in Europe, Buildings account for 40% of the energy consumption and 36% of the CO2 emissions. Energy consumption of the buildings in the US was about 40% of total energy consumption in 2012. Furthermore, in 2015 around 20% of total energy consumption of Australia was associated with residential and commercial buildings.

Modular buildings are the outcome of off-site manufacturing technology in which up to 70% of the construction is carried out in factory. They are factory constructed three dimensional units and transported to the building site. Prefabricated modular construction offers benefits in terms of construction time, cost and waste management. These benefits lead to reductions in materials and energy use and waste during onsite construction. Further benefits are improvement in environmental performance and building overall quality due to standardisation of methods and components.

Previous researches show that up to 70% of buildings' energy consumption is associated with the operational phase. The reduction of energy usage by applying engineered materials and appropriate designs are well documented in the literature. Several studies have been carried out focusing on the environmental performance of residential buildings considering different stages of building life ranging from whole life cycle environmental assessment to merely construction or operation. They have emphasised on various effective factors such as building design, physical properties, passive strategies and occupants. A few researches have been carried out focusing on life cycle costs of prefabricated and modular buildings using life cycle assessment (LCA) method. However, the thermal performance of the prefabricated modular residential buildings is not well documented in the literature. It is necessary to investigate the current baseline performance of these buildings in order to prepare a guideline to improve the new buildings to be constructed in future.

This study investigates the thermal performance of four prefabricated modular buildings as a part of baseline performance evaluation of modular construction in Melbourne, Australia. The materials and systems investigated in this paper are applied in Australian modular construction industry. EnergyPlus was used to simulate the building and estimate the building cooling and heating loads. The main focus of this study is on the building size and envelops design. The results of energy performance simulations for four sample buildings are presented in this paper.

2. THERMAL PERFORMANCE EVALUATION

2.1 Sample buildings

Four floor plans (Wattle, Banksia, Territory and Outback) which are available in the Australian market were investigated. These sample buildings exemplify the typical residential plans constructed by modular construction method. The detailed building data were obtained from the website of a modular construction company in Australia. All selected modular buildings are single story residential buildings. The location considered was Melbourne, Australia. Figure 1 shows the floor plans of the selected buildings. The smallest building is Wattle constructed with only one module (12192 x 3000x 3100 mm at 17 t) and the largest building is Outback constructed of four modules. Banksia and Territory are constructed by using two and three modules respectively.

2.2 Simulation method

The 3D models of the buildings were generated using “OpenStudio” plugins in Sketchup environment. Afterwards all required features of the building were defined in OpenStudio. In this paper the main focus of simulations is to investigate thermal performances for different building sizes. In this respect, other factors that affect the energy consumption of buildings such as location, orientation, annual climate and environmental conditions are considered fixed for simulations. No internal heat loads related to occupancy and equipment were considered. The materials used in building construction, their thicknesses and properties are presented in Table 1.

Figure 1: Floor plans of the four sample buildings

EnergyPlus website provides weather data for different locations based on various data resources. The provided data relevant to the site for Victoria, Australia are based on RMY data source which is Australia representative meteorological year climate files developed by "Australia Greenhouse Office". In order to acquire representative long term data, the weather file was generated by using "Meteonorm". Meteonorm is a Swiss made software providing worldwide weather data in various export formats. Data source used by this software is "world meteorological organization" (WMO) which is providing accurate scientific weather information.

For all buildings 'Ideal Air Load' option was selected in EnergyPlus. The schedules for heating and cooling were defined according to local seasons. According to Lhendup et al the heating season is from 1 May to 31 October; whist the cooling season is from 1 December to 28 February. During the remaining months the heating and cooling systems are not active. The thermostat set points for heating were 21°C during the day (6 am – 10 pm) and 18°C during the night (10 pm – 6 am). The thermostat set point was assigned as 24°C for the cooling season. Table 2 shows the main features of the buildings defined in OpenStudio.

Component	Material	Thickness mm	Conductivity W $m^{-1}K^{-1}$	Density kg m^{-3}	Specific heat J $kg^{-1}K^{-1}$
Exterior Wall	Steel wall panel	1.6	54	7800	450
	OSB board	25	0.13	640	840
	Insulation	90	0.043	91	837
	OSB board	25	0.13	640	840
	Plasterboard	10	0.19	1300	840
Interior Wall	Plasterboard	10	0.19	1300	840
	OSB board	25	0.13	640	840
	Air space	20	-	-	-
	OSB board	25	0.13	640	840
	Plasterboard	10	0.19	1300	840
Floor	Light wt concrete	100	0.53	1280	840
	Membrane	9	0.16	1121	1460
	Cement Mortar	15	1.60	2000	1000
	Vinyl covering	15	17	1390	900
Roof	Metal roofing	1.5	45	7680	418
	OSB board	25	0.13	640	840
	Insulation	17	0.049	265	836
	Roof membrane	9	0.16	1121	1460
	Gypsum	12	0.16	784	830
Interior Door	Wood	25	0.15	608	1630
Exterior Door	Metal Surface	0.8	45	7824	500
	Insulation board	25	0.03	43	1210

Table1: The properties of selected materials for each components of the building

Category	Item	Value
Location, Melbourne, Australia	Latitude [deg]	-37.817
	Longitude [deg]	144.967
	Time Zone [h]	10
	Elevation above sea level [m]	38
	Site ground temperature [°C]	18
Window glazing	U-Factor [W m^{-2} K^{-1}]	2.10
	Solar transmittance [-]	0.237
Thermostat settings	Heating set point:	Day:21°C, Night:18°C
	Cooling set point:	24°C
Space infiltration rate	Flow per space floor area [ms^{-1}]	0.0007
Design ventilation rate	Outdoor Air flow per floor area [ms^{-1}]	0.0003

Table 2: Main features of the buildings defined in OpenStudio

3. RESULTS AND DISCUSSION

3.1 Effect of building size

Building size can affect the total energy consumption and energy consumption per unit floor area. While the total cooling and heating loads tend to increase by growth of building size, the loads per floor area is expected to decrease. Table 3 shows the total floor area and floor area of conditioned spaces for four sample buildings. The conditioned spaces are living room, bedrooms and study rooms for which 'Ideal Air Load' option has been set in EnergyPlus. The unconditioned spaces include the bathrooms and storages. Table 3 shows that the ratio of conditioned spaces has been decreased as the total floor area increases. While 92% of the spaces in the Wattle building are conditioned, this percentage decreases to 85% in the Outback.

Building	Area (m^2)				Window to wall ratio (%)				
	Floor	Conditioned	Walls	Window	North	East	South	West	Overall
Wattle	40.2	36.9	85.21	11.75	3.74	27.88	3.64	78.38	14
Banksia	68.4	61.8	104.12	6.91	9.26	5.04	5.61	5.04	7
Territory	109.7	94.4	116.56	12.34	7.03	14.69	3.33	21.01	10
Outback	135.7	114.8	148.20	18.34	30.55	4.84	11.33	5.15	12

Table 3: Areas and window to wall ratios of the buildings investigated

3.2 Effects of wall to window ratio and conditioned area

The components and configurations of building envelope highly affect the energy consumption of the buildings. The location and size of the windows, the construction of exterior walls and roof, window and wall areas and the window-wall ratio are some of the envelope parameters that highly affect the amounts of heat gain in summer and heat loss in winter. An increase in window area especially on north façade can increase the cooling load during summer. Table 3 shows the window and wall areas as well as window to wall ratios on the exterior walls facing different directions for all simulated buildings.

Banksia has smaller window area than Wattle which causes a dramatic fall in window to wall ratio of Banksia (see Table 3). Wattle has large windows and a big glass door on the east and west façade respectively. Regarding the fact that Wattle is the smallest building and therefore wall area is lower than other three buildings the high value of window to wall ratio can be justified.

3.3 Cooling and heating loads

The simulations of four sample buildings were carried out in order to evaluate the thermal performance. According to the results, the cooling load is considerably lower than heating load for all buildings. This is due to the climate conditions of Melbourne in which the heating season is longer and more heating load is required to fulfil indoor thermal comfort. The annual cooling load is maximum among all simulated buildings for Wattle being equal to 0.43 GJ. This can be explained due to higher window to wall ratio and larger total surface area to volume ratio which can result in higher load per unit floor area. The annual cooling load per unit area for Bankisa, Territory and Outback are relatively close (0.18, 0.17, and 0.19 GJ respectively). The cooling load for Banksia is slightly higher than the one that of Territory. This can be explained by the fact that the window to wall ratio on north façade is higher for Banksia which caused more heat gain during the summer. The heating load increases with a rise in total building area. Since window area has less influence on heating load compared to cooling load, the heating load increased consistently from Wattle to Outback The values of annual heating loads are 13.08, 21.06, 26.09 and 33.25 GJ for Wattle, Banksia, Territory and Outback respectively. The maximum and minimum cooling loads occur during January and December respectively. The heating load is maximum in July and minimum in October.

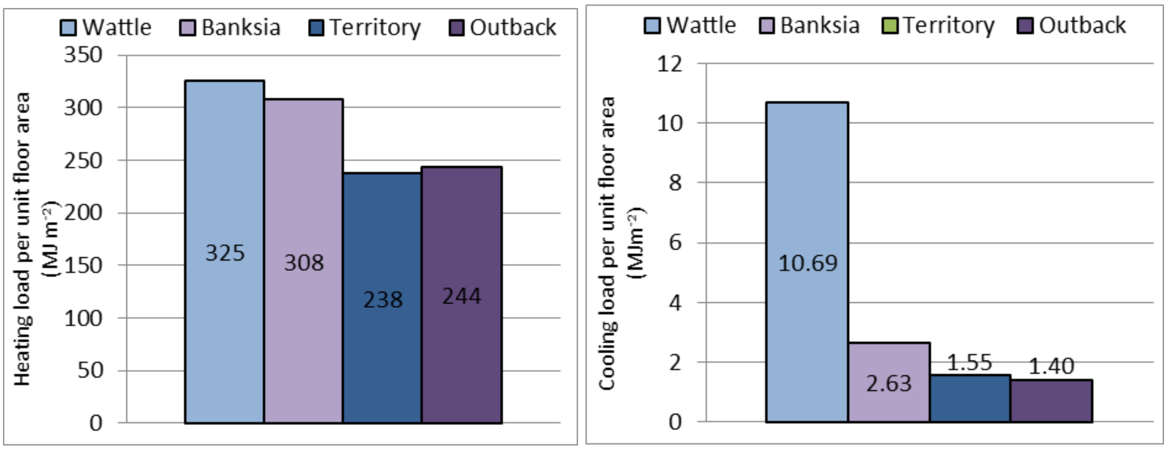
Figures 2a and 2b show the values per unit floor area for heating and cooling loads respectively. The heating energy per floor area decreases with the rise in the floor area. However, it increases slightly from "Territory" to "Outback". This pattern verifies the fact that rather than floor area other factors such as building envelope design parameters can influence the energy consumption of the buildings. For instance, the addition of shading devices can significantly reduce the cooling load since it limits the amount of solar heat gain received from glazed areas. Similarly the glazing type and properties of glazing affect the heat transfer between indoor and outdoor environments and the heating and cooling loads accordingly [25]. Building orientation is another factor that affects the building energy consumption since the amount of solar heat gain can vary by changing the orientation. Other factors such as occupation and compartmentalisation can affect the building loads. However, the occupancy was not considered in this paper. Also compartmentalisation is expected to have small impact on the loads of the sample buildings investigated in this paper. Cooling load per unit floor area decreases consistently with increasing floor area (Figure 2b). To justify the change in heating load per unit floor area the trend of increase in floor area as well as window to wall ratio should be considered.

The sharp change in the cooling load between Wattle and Banksia can be explained by considering the high amount of total cooling load for Wattle. Since the total cooling load of other three buildings were of close values, the consistent reduction of the cooling load per floor area from Banksia to Outback is reasonable.

Figure 3 shows the annual electricity consumption per floor area for the sample buildings. These values have been calculate according to peak demand of each building and by selecting appropriate equipment with adequate capacity from Australian energy star rated equipment list. Table 4 provides the capacities, cooling and heating coefficient of performances (COPs) of the heat pumps selected. It is apparent from Figure 3 that the electricity consumption per floor area decreased consistently from Wattle to Territory, but increased from Territory to Outback. The increase in the electricity consumption for Outback is due to the lower COPs of the heat pump available and selected to meet the higher peak loads (see Table 4).

Building	Heat pump model	Heating (kW)	Heating COP	Cooling (kW)	Cooling COP
Wattle	Daikin FFQ25C2 / RXS25K3	3.2	4.00	2.5	4.46
Banksia	Daikin FTXM50P / RXM50P	6.0	4.23	5.0	4.24
Territory	Daikin FTXM60P / RXM60P	7.0	4.07	6.0	3.87
Outback	Daikin FTXS71L / RXS71L	8.0	3.67	7.1	3.41

Table 4: Capacities and COPs of heat pump selected



(a) (b)

Figure 2: (a) Heating and (b) Cooling load per unit floor area for all simulated buildings

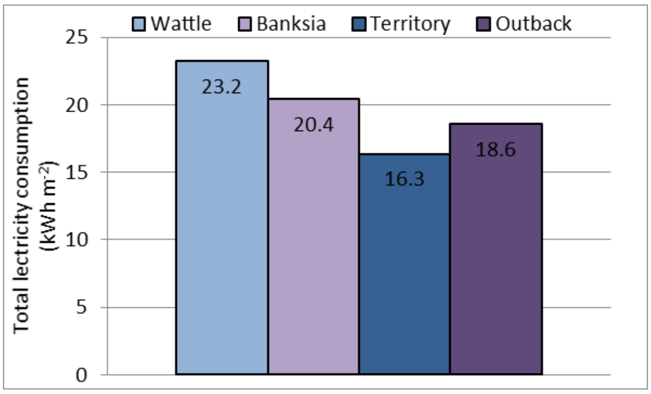


Figure 3: Annual electricity consumption

4. CONCLUSION

In this paper energy performance simulations of four prefabricated modular houses have been carried out using EnergyPlus interface with OpenStudio. The buildings have been selected from a supplier available on the market. The number of selected sample buildings was limited to four which are representatives of single family residential houses with different floor areas. A larger number of sample buildings that could provide better opportunity for more expanded results and discussion is to be considered in future works. Except building envelope parameters and floor area all other effective factors have been remained constant throughout the simulations. The heating and cooling seasons for Melbourne have been defined according to literature and applied in the simulations.

The results reveal that heating and cooling load of the buildings highly depend on both floor area and window to wall ratio. While the energy required for heating showed increase in buildings with larger floor area, the cooling load followed a different pattern that indicated the impact of envelope parameters. Results showed that for Melbourne climate the heating load is significantly larger than cooling load. The monthly results show that the highest heating load occurs in July for all buildings. The highest cooling energy is consumed during January for all buildings. The heating and cooling energy per floor area show a decreasing trend with increase of floor area. Results also indicate that window to wall ratio has higher impact on cooling load compared to heating load.

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