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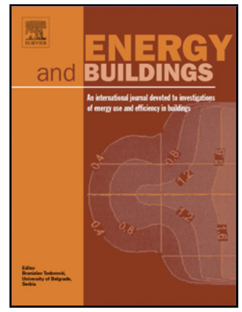

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Highlights:

1. Optimization of a hypothetical insulated cavity rammed earth wall house was conducted

2. Small windows and large window shadings are desirable in hot arid climates

3. Large north windows/small other windows are desirable in warm temperate climates

4. Small windows and shadings result in low life-cycle cost in cool temperate climates

5. Thin walls and insulations lead to minimum life-cycle cost in all three climates

Design optimization of insulated cavity rammed earth walls for houses in Australia

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Abstract

This paper presents an optimization study of the design parameters for houses using rammed earth walls, including window sizes, window shading, the amount of thermal mass and the amount of insulation in the external walls. The optimization is based on two objectives: (1) energy use reduction and (2) life-cycle cost minimization.

It was found that, in general, the thicker the walls/insulation was applied, the less the energy load, but the higher the life-cycle cost. In hot arid climates, small windows and large window shadings lead to a lower energy load while the minimum life-cycle cost was achieved with the smallest window and window shading. In warm temperate climates, the optimum size of north facing window was 30% and 40% of the wall area to achieve the minimum energy load and life-cycle cost while the sizes of the windows on the other walls as well as the window shading needed to be as small as possible. In cool temperate climates, small south facing windows and large windows in the other walls would result in the lowest energy load; however, to achieve the minimum life-cycle cost, all the windows and window shadings should be as small as possible.

Keywords: rammed earth, parameter optimization, energy load, life-cycle cost, Australia climates

1. Introduction

Buildings in Australia, including residential premises, are important contributors to greenhouse gas emissions and climate change [1, 2] where the residential sector consumes 8% of the total energy use [3] and more than 40% of this consumption is used for space heating and cooling [4]. Therefore, the development of residences containing low embodied energy and which require little energy for space heating and cooling is of prime interest to architects and builders.

Rammed earth (RE) wall houses are perceived to be sustainable as they carry extremely low embodied energy, in particular when locally available material is used [5-7]. In addition, with their large thermal mass, RE wall houses are assumed to perform in a thermally desirable manner because the mass can effectively delay the heat transmission through the external walls, particularly in summer when peak indoor temperatures are delayed by a long thermal time lag. In a relatively mild climate without extended periods of heat or cold, energy conservation can be achieved and temperature smoothed out [8-10]. Moreover, a study conducted by Allinson and Hall [11] indicated that RE walls can potentially save the energy for indoor humidification.

Such perceptions of RE walls mean that their construction has attracted increasing interest recently as architects develop greater interest in sustainability principles. However, considered more realistically, the smoothing of the temperature in mild climates is offset by the fact that when summer and winter are more extreme (hot and cold for long periods), the low thermal resistance (R-Value) of RE could result in poor thermal performance. Once the interior space is warm during several hot days, it is difficult to cool unless night-time ventilation is applied. In cold days the earthen material does not effectively prevent heat draining from the inside to the outside of the house, which means that a large amount of energy may be required for space heating. Because of this behaviour, it is currently difficult for house designs using only RE walls to satisfy the Deemed-to-Satisfy provisions of the Building Code of Australia within the Australian National Construction Code (NCC) [12], which require a minimum R-value for external walls of 2.8m²K/W for Class 1 buildings (detached residential) for all climatic zones in Australia except the Alpine zone, where the minimum requirement is 3.8m²K/W. According to previous studies [13-16], a typical 300mm thick RE wall has an R-Value of only 0.27- 0.70m^{2}K/W. The NCC has an alternative requirement for external walls with a surface density greater than 220kg/m^2, which states that an equivalent wall insulation with an R-Value of 0.5 to 1.0m²K/W (depending on other design parameters) shall be added. A typical 300mm thick RE wall has a surface density much greater than 220kg/m^2 (usually between 540 and 660kg/m^2 [16]). Thus insulation with an R-Value of 0.5 to 1.0m²K/W is required for solid RE walls in all climate zones except for the Alpine zone.

2. Insulated cavity RE walls

For RE, rigid insulation (extruded polystyrene or polyisocyanurate) can be inserted in the middle of the wall to preserve the aesthetics of the wall surfaces [17]. Extruded polystyrene

(XPS) with a thickness of 1m has an R-Value of 28.6-40.0m²K/W [18]. If the average value of 34.3m²K/W is applied, a solid RE wall would need to be insulated by XPS with a thickness of 15 to 30mm, in order to satisfy the minimum R-value requirement of the NCC.

Although adding 15mm to 30mm thick XPS insulation enables RE wall houses to meet the minimum R-Value requirement of the BCA, it does not guarantee satisfactory thermal performance without taking into account the other design parameters including window size, window shading, insulation thickness and the amount of thermal mass [19]. The effects of insulation as well as these other design parameters on thermal performance are discussed in the following sections of this paper.

3. Star rating requirement and methods for reducing energy load

There is another option for Class 1 buildings (residential) to satisfying the requirement of BCA [20]: the Energy Efficiency requirement, also known as the star rating method. There are 10 star ratings (1 to 10) in the Nationwide House Energy Rating Scheme (NatHERS), where more stars correspond to less energy loads. Note, in the BCA, the star rating is based on predicted space heating and cooling loads only, hence the star rating bands vary according to climatic regions. Other energy demands such as domestic hot water (DHW) are not included. According to the NatHERS, Australia is divided into 69 climate regions of similar climate; each is represented by a city with typical local climate condition. For example, in Adelaide (climate region 16: warm temperate climate), the 6-star rating corresponds to a maximum energy load of 96MJ/m^2 per annum, while in Ballarat (climate region 66: cool temperate climate) the 6-star rating corresponds to an energy load of 197MJ/m^2 per annum. By comparing the predicted energy loads for heating and cooling in order to maintain indoor thermal comfort to the reference value for each star rating load, a building design can be assigned a star rating. Starting from 2010, new residential buildings have been required to meet a 6-star rating as a minimum. In other words, the total predicted energy load for heating and cooling of the building must be equal to or less than the maximum allowed for each climate region for a 6-star rating.

Passive design strategies such as direct solar gain for passive heating and natural ventilation for passive cooling are effective to reduce the heating and cooling loads, respectively [21, 22]. The direct gain strategy requires a large amount of thermal mass to absorb and store solar heat that comes through the windows during the day and to release this stored energy slowly during the night [22]. Natural ventilation (for example opening windows when the outdoor temperatures are lower than indoors) helps to cool a house and reduces the cooling load [21]. In order to effectively implement these passive strategies, the windows must be sized accordingly as a large amount of heat flow between the inside and outside of a building as well as the natural ventilation in a building is transferred through windows. Window shading should also be taken into account as it controls the amount of solar gain through the windows. In summary, many researchers have confirmed that substantial energy saving on space heating and cooling can be obtained through optimised window design [23, 24] and proper use of thermal mass and insulation [25-27].

4. Investigations

The study aims to investigate the relationships between each parameter and the energy loads as well as total life-cycle cost, thus providing information for designers and house owners to make strategic design decisions. For example, small window areas in some climates can result in low energy loads; however, the occupants may prefer large windows for better natural light or frame view. With the information provided by this study, occupants can make more informed decisions by balancing the advantages and costs of increasing window size. It should be noted that the recommendations provided from this study are for residential buildings. For other building types (such as office buildings), the basic model as well as the assumptions of the simulation should be modified accordingly. In order to achieve this aim, the following objectives need to be fulfilled:

a) Quantify the effects of four design parameters on the heating and cooling loads of hypothetical RE houses. They are: (1) the size of each window in relation to the walls (window to wall area ratio, WWR); (2) the window shading (expressed as the projection factor, which is the ratio between the width of window shading and the distance between the bottom of the window shading and the window sill, as shown in Figure 1); (3) the amount of thermal mass (RE wall thickness); and (4) the amount of external wall insulation (insulation thickness); and

b) Evaluate the effect of each parameter on the total life-cycle costs which comprise the initial cost for construction (including air conditioner/heater) and the running cost (for space heating and cooling).

The options for each parameter were:

- *Window to wall ratio:* Five options of the WWR were evaluated – 10%, 20%, 30%, 40% and 50%. The minimum value 10% was selected considering that the house needs some natural light and ventilation. The maximum value 50% is restricted by the wall length as the window area was determined by the window width which is limited by wall length. The window sill and height were kept constant.

- *Projection factor:* the window shading was assumed to be 0.2m above the top of window. Five options for window shading (projection factor) were considered, from no window shading (projection factor 0, corresponding to an eave width of 0.00m) to large window shading (projection factor 0.60, corresponding to an eave width of

1.00m), incrementing by 0.15 (corresponding to an increment of eave width of 0.25m). Larger window shadings were not considered as it would prevent the house from obtaining sufficient daylight.

- *RE wall leaf thickness:* Four thicknesses were considered for each RE wall. The thicknesses ranged from 150mm to 225mm, incrementing by 25mm, as according to local builders it is difficult to construct wall leaves thinner than 150mm nor wall leaves thicker than 225mm are not usually applied for insulated cavity RE houses due to the fact that overly thick RE walls are not economical and will sacrifice the usable floor area. When investigating the effect of internal or external wall thickness, the other wall leaf thickness (150mm) and the insulation thickness (30mm) were kept constant as shown in Figure 2.

- *Insulation thickness:* Eight options of insulation thickness were considered, ranging from 30mm to 100mm, incrementing by 10mm. A 30mm polystyrene insulation gives an R-Value of approximately 1.0m^{2}K/W which is the minimum requirement for added insulation of external walls with surface density over 220kg/m^2 and insulation thicker than 100mm are not practical according to local builders. When investigating the effect of insulation thickness, the internal and external RE wall leaf thicknesses (150mm) were kept constant as shown in Figure 3.

5. Methods

The heating and cooling load was simulated using the energy rating software *AccuRate* [28]. *Accurate* calculates the annual heating and cooling energy loads required to maintain thermal comfort in a model building, taking into account the building parameters, location and assumed usage of the building. The software was developed by CSIRO and is accredited for use in NatHERS. The accuracy of this software has been validated both empirically and through intermodal comparisons [29-32]. The mathematical basis of this energy rating tool can be found in the work of researchers such as Walsh and Delsante [33], and the detailed assumptions embedded in this software about weather data, internal gains, infiltration, use of heating and cooling and the window opening schedule are explained by the authors in a previous article [34].

Life-cycle costing in the current study was a combination of the initial cost of construction (including the cost for air conditioner) and the running costs (for space heating and cooling). The detailed calculations are presented in Section 5.3.

5.1 "Base case" model house

This study uses a one-zone building as it is common to analyze and simulate thermal performance of houses using simplified models [30, 32]. Table 1 lists the characteristics for the base case house of an insulated cavity RE wall house. The results for this base case house will be the reference point for comparing the effect of changes to design parameters. A diagram of the base case house is shown in Figure 4 where it can be seen that the base case house was a north facing single zone house with no window shading. WWR of 10% for each direction was applied. It should be noted that according to NCC, the minimum required glazed area for habitable rooms is 10% of the floor area. For the base case house in this study, the overall glazed/window area was 10.8m^2, which was more than 10% of the floor area of 96m^2. The pitched roofs had an angle of 30^o. Extruded polystyrene was selected as insulating material of the walls. The other design parameters of the basic model are simplified (e.g. highly insulated ceilings and standard concrete floor) so that effects of these components are minimized.

Similarly, no partition walls (commonly constructed by lightweight materials) were applied in the base case house as their impact on the optimization analysis of external walls is minimal as they only affect the heat transfer between two adjacent zones and not the heat exchange between the inside and outside of a house. Moreover, in practice, internal or partition walls may be placed anywhere depending on different designs while the zone types vary according to the designer and house owners (e.g. the living room may not necessarily be planned on the north side).

A test simulation has been conducted to investigate the effect of internal walls on the energy loads of a model house. The result showed that internal walls had little impact. For example, in Adelaide, the single zone basic model house has an energy load of 275.0MJ/m^2 per annum, while a 3-zone model house with the same floor area (internal wall type: brickwork) has a similar energy load of 280.1MJ/m^2 per annum, as long as all the other factors were the same.

With *AccuRate*, a factor that would affect the energy loads of multi-zone houses was the heating thermostat setting, which varies according to the zone type (the cooling thermostat was independent on zone type). In other words, it was actually the zone type instead of the application of partition walls that affects the energy loads of houses. In this study the zone type was assumed to be Living/kitchen (which is required for one-zone model analysis by *AccuRate* program as internal heat gains from occupants and equipment can be considered in this zone type) and the heating thermostat setting for this zone type is 20^{o}C.

The test simulations however found that the optimum values of the design parameters were independent of the thermostat settings. It can therefore be concluded that the simple model house can be used to conduct the parametric study in this research.

5.2 Australian climate zones

For the analysis, three locations were considered – Longreach, Adelaide and Ballarat– covering Australia climate zones 3, 5 and 7 (as shown in Figure 5), corresponding to semi-arid climate (Bsh), hot Mediterranean climate (Csb) and moderate oceanic climate (Cfb) in the Koppen climate classification system, respectively. Detailed information about these climate zones is available from the NCC [12] which is summarized in Table 2. The maximum energy load demand to satisfy the 6-star rating requirements of the NCC [12] is presented in Table 2 for each of these locations.

5.3 Life-cycle cost analysis

5.3.1 Initial cost

The price of constructing RE walls (maximum storey height of 3m) is commonly calculated by wall area according to contractors who were consulted during the current study. In real life situations, the labour component will be built-in. For the purposes of the current study, this labour cost was assumed to be independent of the wall thickness so that only the quantity of the materials was responsible for any price differences in the study calculations. The price of each building parameter was provided by the contractors or derived from quotes provided by Rawlinson's Quantity Surveyors and Construction Cost Consultants [35]. The standard construction costs in Adelaide, South Australia, were used for all calculations (as shown in Table 3); whereas the price of some building parameters in Longreach and Ballarat were not available. The prices of building parameters in different cities will not affect the investigation of this research. The inflation rate (2.75%) and interest rate (4.75%) used in this analysis was the average value of Australia inflation rate for the last 10 years (2004-2013) [36, 37].

Data for the air conditioner modelling in the current study were obtained from standard reverse cycle machines which have extremely high efficiency. Reverse cycle air conditioning was selected for the heating/cooling system as it was the most popular system for cooling and heating (reverse cycle heat pump system) in Australia according to a 2012 survey [38]. Its size was based on the peak heating and cooling load and the price reflected the machine's capacity to cool or heat. Prices of common reverse cycle air-conditioners and their capacity were obtained from local market, which can also be obtained online [39]. The relationship between the capacity and price of a reverse cycle air conditioner is illustrated in Figure 6 where the cooling capacity ranged from 2.0kW to 12.5kW and the while heating capacity ranged from 2.7kW to 14.0kW). The equations presented in Figure 6 are polynomial equations for the trend lines of the selected data. The symbol '$' represents the Australian Dollar.

The initial cost of construction of the model houses (C_{IC}) consisted of the cost of constructing the RE walls (C_{RE}), the cost of insulation materials (C_I), the cost of windows (C_W), the cost of window shading (C_S) and the cost of air conditioning (C_{AC}), which can be computed as: $C_{IC} = C_{RE} + C_I + C_W + C_S + C_{AC}$.

The cost of window eaves and windows were based on their dimensions. Once the windows were sized, the volume of RE and insulating material could be determined based on the net wall area and wall thickness, and then the cost of RE walling and insulation material could be determined. For each model, the peak heating and cooling load was determined using *Accurate*. Based on the peak load, a virtual air conditioner was devised and its price was then derived from the relationship given in Figure 3.

5.3.2 Running cost for heating and cooling

Running cost (C_R) depends on the cost of heating (C_H) and cooling (C_C), which can be expressed as: $C_R = C_H + C_C$; the annual cost for heating/cooling of a house can therefore be calculated as: $C_H = N \times P_H/E_H$ and $C_C = N \times P_C/E_C$, where N = the amount of energy consumed for heating or cooling annually; P_H, P_C = the unit price of electricity for heating (in winters) and cooling (in summers), respectively; E_H, E_C = the heating coefficient of the performance and cooling energy efficiency of the reverse cycle air conditioner, respectively. The actual (present) value (C_a) of C during the life-cycle of the building can be calculated by [27, 40, 41]: $C_a = C \times (1+g) \times [1-(1+g)^n/(1+i)^n]/(i-g)$ (if i>g), where g = the inflation rate; i = the interest rate; n = the assumed life-time of the building.

For each model house with given input data, the annual heating and cooling load were calculated and the annual cost of heating and cooling was determined. As a result, the running cost of the model house over its life-cycle could be calculated. Values of the parameters used in the calculation, based on local market conditions, are provided in Table 3.

6. Simulation results

The simulation results show that the dwelling in warm temperate climates (Australian climate zone 5) required both cooling and heating. In hot arid climates (Australian climate zone 3), however, space heating was hardly required; almost all the energy was consumed for space cooling. In cool temperate climates (Australian climate zone 7), space cooling accounted for a very small proportion of the total load (always less than 3%) and space heating consumed most of the energy.

6.1 Warm temperate climates (such as Australian climate zone 5: Adelaide)

6.1.1 Effect of window size

As illustrated in Figure 7, increasing the size of the north window decreased the heating load considerably as the north facing window was able to collect solar heat in winter. This, however, would increase the cooling load in summers with heat entering the house through the large north windows. The minimum total load over the year was achieved when the north window size was 40% of the wall area. East and west window sizes had similar effects on the energy loads as shown in Figure 7b and 7d. Increasing the size of these two windows lowered the heating load and raised the cooling load with the total load also being increased because the cooling load increase outweighed the drop in the heating load. Enlarging the south window (Figure 7c) increased both the heating and cooling loads particularly due to the increase in cooling due to the heat gains late in the afternoon when the sun could still reach the south-facing windows.

6.1.2 Effect of window shading

Figure 8 shows that increasing the projection factor of window shading resulted in a considerable increase in heating load and a small reduction in cooling load. As the projection factor increased from 0 to 0.60, the total energy load increased from 75.3 to 92.9MJ/m^2 per annum due to an increased heating load.

6.1.3 Effect of RE wall thickness

As illustrated in Figure 9, only a slight reduction in the total energy load (less than 4%) was achieved by increasing either the external or internal RE wall leaf thickness from 150mm to 225mm as the total thermal property of the original walls only changed slightly with an increase by 75mm of thermal mass. Despite the claims that RE walls provide excellent thermal mass effect, this investigation found that the benefit of having thicker RE walls is small.

6.1.4 Effect of insulation thickness

As shown in Figure 10, increasing the insulation thickness for the hypothetical house in Adelaide (Australian climate zone 5) from 30mm to 100mm reduced both the heating and the cooling load, and the total energy load dropped by 36% from 75.3 to 48.4MJ/m^2 per annum as the increased thermal resistance that can effectively reduce the heating load.

6.1.5 Meeting the 6-star requirement

In summary, in a warm temperate climate (Australian climate zone 5) where space heating consumes more energy than space cooling, strategies which can effectively reduce the heating load are desirable, such as applying large north windows and small other facing windows, minimising the eave width and maximising the insulation thickness. Increasing wall thickness can only slightly reduce the energy load thus it is not recommended to reduce energy loads by constructing very thick walls.

It should be noted that the energy loads presented in Figures 7 to 10 were calculated value. The star rating was assigned based on the area-adjusted load, which was calculated by adjusting the total load in proportion to the total building surface area to floor area ratios of a range of dwellings in a particular Climate Zone [42]. From the data presented above, the maximum total energy load of 99.2MJ/m^2 per annum occurred when the WWR for the south window was 50%. The area-adjusted load for this calculated value was 80.8MJ/m^2 per annum, which was lower than the maximum demand of 6-star rating (96MJ/m^2 per annum) for this climate. This means that for the base case house, each option of these four parameters investigated in this study can be applied in this climate.

6.2 Hot arid climate (such as Australian climate zone 3: Longreach) and cool temperate climate (such as Australian climate zone 7: Ballarat)

6.2.1 Effect of each parameter on the total energy loads

Since the heating load in hot arid climates (Australian climate zone 3) and the cooling load in cool temperate climates (Australian climate zone 7) accounts for a very small part of the total energy load, only the total energy load was analysed as shown in Figure 11.

In hot arid climates (Australian climate zone 3); the window size in each direction has a similar effect on the total energy load. Increasing the WWR from 10% to 50% caused in all instances a significant rise in the total energy load from 89.0 to approximately 140.0MJ/m^2 per annum. Increasing the projection factor is an effective way to reduce the total energy load in hot arid climates, whereas when the projection factor increased from 0 to 0.60, the total energy load dropped by 16% from 89.0 to 74.9MJ/m^2 per annum due to the fact that in this climate zone, space heating is rarely required and large window shading can effectively reduce the cooling load. RE wall thickness had only small effect on the total energy load, while an increase of insulation thickness from 30mm to 100mm reduced the energy load by 16%.

In cool temperate climates (Australian climate zone 7), the east and west window sizes had only a very slight effect on the total energy load. Increasing the WWR of the north facing window from 10% to 50% led to a substantial drop (by 18%) in the total energy load, while increasing the WWR of south facing window resulted in a considerable increase (by 12%) in the total energy load. Increasing the projection factor from 0 to 0.60 resulted in a rise of the total energy load by 14% from 268.0 to 306.1MJ/m^2 per annum due to the fact that in this climate most of the total energy load was used for space heating and larger shadings reduced the amount of solar heat entering the house hence the increased the heating load. The efffect of RE wall thickness on the total energy load in this climate was similar to that in hot arid climates. Insulation thickness, however, had greater effect in cool temperate climates (an increase from 30mm to 100mm reduced the energy load by 26%) than that in hot arid climates.

6.2.2 Meeting the 6-star requirement

In summary, in a hot arid climate (Australian climate zone 3), considering all changes investigated in this study, the maximum calculated energy loads of the base case house (140.0MJ/m^2 per annum) was achieved when the WWR of the east facing window was 50%. The area-adjusted load for this calculated value was 119.9MJ/m^2 per annum, which was still lower than the maximum demand of 6-star rating (141.0MJ/m^2 per annum) for this climate, meaning that for the base case house, all the changes investigated in the study can be applied.

In a cool temperate climate (Australian climate zone 7), however, the base case house can achieve the 6-star rating requirements only when the WWR of the north facing window was 30% or above, or when the insulation thickness was 50mm or more. Changing the values of the other parameters, individually, however, cannot help the base case model to meet the 6-star rating requirements unless some of the other parameters were also changed. For example, if the WWR of the north facing window is smaller than 30% (which makes the base case model fail to meet the 6-star rating requirements), the base case house can still meet the 6-star rating requirements if the insulation thickness is changed to be more than 30mm.

7. Effect of each parameter on the total life-cycle cost

In order to reduce the total energy load or to meet the 6-star rating requirements, the design parameters must be optimized; however, changing the value of the parameters may results in an increase of total life-cycle cost. For example, increased insulation thickness will reduce the total energy load and therefore the running cost for heating and cooling, but doing so will increase the cost of insulation material. If the increase in the material cost outweighs the reduction in the running cost, the total life-cycle cost will increase. Hence in order to minimize the total life-cycle cost, the effect of each parameter on the total life-cycle cost has to be investigated. For example, in hot arid climates, small windows on each wall will result in lower energy loads, but in practice large windows are commonly favoured by the occupants in order to capture natural light, to frame views and to augment heating. Increasing the window size may however increase the total energy load, but as long as the total energy load can be kept under the maximum allowable for a 6-star house by changing other parameters (for example increasing the insulation thickness), then large windows are acceptable. In this case, what designers will be more interested to know is the implication of increasing the window size/insulation thickness on the total life-cycle cost. If the increase in the window size and insulation thickness will only result in a small increase of the total life-cycle cost then large windows may be chosen.

7.1 Warm temperate climates (such as Australian climate zone 5: Adelaide)

Figure 12 shows an example of the effect of a design parameter (north window size) on the economic costs of rammed earth houses in climate zone 5. In general, the initial cost of construction and air conditioning has the most significant impact on the total life-cycle cost, while the cost for heating and cooling only accounts for a small portion of the total life-cycle cost due to the fact that reverse cycle air conditioners have very high efficiency.

It can be seen from Figure 12 that the minimum life-cycle cost occurs when the north window size is 30% of the wall area. The effects of the other three window sizes and window shading on the economic costs are reported in Table 4. For the east, south and west windows, the smallest window size (WWR=10%) gave the minimum life-cycle cost although the life-cycle cost did not increase considerably (no more than $620) when the window sizes (east, south and west) increased from 10% to 30%. This means having larger windows in these walls does not have much of an impact on the total life-cycle cost of the house. Increased window shading (expressed in the projection factor) resulted in an increase in energy load, and therefore increased running costs (21%). The initial cost also increased because of the larger eaves. Hence the total life-cycle cost of the building increased due to the increase in both running and initial costs.

The effects of RE wall leaf and insulation thickness on the costs are presented in Table 5 where it can be seen that the external and internal RE wall leaf thicknesses had only a small effect on the running cost. For example, increasing the external wall thickness from 150 to 225 mm only reduced the running cost by 3%. The life-cycle cost, however, increased by 18% as each wall thickness increased from 150 to 225mm. Hence thinner RE wall leaves are recommended as long as they can fulfil the building's structural strength requirements [13, 43]. The running cost decreased by $1028 (36%) while the total life-cycle cost increased by $4390 (9%) with the gradual increase in thickness from 30mm to 100mm because the increase in the initial cost due to the extra insulation was more than the decrease in the present value of the running cost.

7.2 Hot arid climates (such as Australian climate zone 3: Longreach) and cool temperate climates (such as Australian climate zone 7: Ballarat)

7.2.1 Effect of window size

In hot arid climates (Australian climate zone 3), increasing the size of each window led to both greater initial costs and greater running costs, meaning an increased life-cycle cost for the building as shown in Table 6. As the WWR increased from 10% to 50% for north, east, south and west windows, respectively, the life-cycle cost increased by $2527, $2720, $2677 and $3051, respectively. In cool temperate climates (Australian climate zone 7), however, increasing the north WWR up to 50% would slightly decrease the total life-cycle cost, and increasing east or west WWR up to 30% (50%) will only increase the total life-cycle cost by 1% (2%). What is important to note, however, is that in order to meet the 6-star requirements, the WWR of the north facing window of the base case house should be no less than 30%, and the larger the better.

7.2.2 Effect of window shading

As can be seen from Table 7, in hot arid climates (Australian climate zone 3), increasing the projection factor from 0 to 0.60 resulted in a 16% reduction in running cost. The minimum initial cost and life-cycle cost were achieved at a projection factor of 0.45. In climate zone 7, however, increasing the projection factor increased both the initial cost and the running cost because the shading would reduce the amount of solar radiation into the space in winter, hence increasing the heating energy. Life-cycle cost increased by $1722 as the projection factor increased from 0 to 0.60.

7.2.3 Effect of wall leaf thickness

Running costs could not be reduced to any great degree by increasing either the external or the internal wall thickness whereas increasing the wall thickness significantly raised the initial cost. Consequently, in hot arid climates, the total life-cycle cost increased by 17% (14%) when exterior (interior) wall leaf thickness increased from 150mm to 225mm as shown in Table 8 and Table 9. In cool temperate climates (Australian climate zone 7), similar results were observed with total life-cycle costs increased by16% when each of the wall leaf increased from 150mm to 225mm.

7.2.4 Effect of insulation thickness

Table 10 shows that in hot arid climates (Australian climate zone 3), increasing the insulation thickness from 30mm to 100mm can reduce the running cost by 16%, while the initial cost and total life-cycle cost were minimized at an insulation thickness of 40mm. In cool temperate climates (Australian climate zone 7), it is clear that increasing the thickness of the insulation from 30 to 100mm also led to a steady drop in running costs (up to 24%) but raised the initial and total life-cycle costs by 13% and 6% respectively. It is important to note that insulation with a sufficient thickness (50mm for the base case house) must be applied in order to meet the 6-star rating requirements. Although increasing the insulation thickness will result in an increase of total life-cycle cost, the total energy load can be considerably reduced while the cost penalty from increasing insulation thickness is not significant (the total life-cycle cost will only increase by approximately 1% for every 10mm increase in insulation thickness). Hence if the total energy load of a house exceeds the maximum value for 6-star rating requirements, it is recommended that insulation thickness be increased in order to reduce the energy load (to a value that is lower than the maximum allowance for 6-star requirements).

8 Multiple parameter study

Multiple parameter study was conducted to investigate the optimal thermal performance of fully optimised ICRE wall houses. To achieve this aim, once the optimum value (in terms of total energy load) of a parameter was determined, it was applied in the subsequent investigations of the other parameters. The results show that the optimum value of each parameter for the multiple parameter study was the same as that for single parameter study; except for the east and west window size for model house in cool temperate climate (for multiple parameter study, the optimum value of both east and west window size was 10% of the wall area, whereas for single parameter study, the optimum values for east and west window size was 50% and 40% of the wall area, respectively).

In terms of the life-cycle cost, the optimum value of each parameter for multiple parameter study was the same as that for single parameter study. In general, small value of each parameter results in low life-cycle parameter. It should be noted that in order to meet the 6-star rating requirement, in cool temperate climate, the north window size should be no less than 30% of the wall area, or the insulation thickness should be larger than 50mm, or the external walls of the house was insulated with 40mm insulation with a north window size larger than 20% of the wall area. Among these three options, having large north window (more than 30% of the wall area) lead to the minimum life-cycle cost.

9 Conclusions

The present study aims to provide the relationship between each parameter and energy loads/life-cycle cost, so that designers and house owners can make more informed decisions by balancing personal preferences with the cost of implementing them. In order to achieved this aim, an analysis of the energy efficiency and economic costs of RE houses was conducted by examining different options for the design parameters across a range of climate zones (from hot arid to cool temperate). The optimum value of each design parameter (from the minimum energy load/total life-cycle cost point of view) was determined with reference to the base case house developed for this study. This means that when the design parameters for the base case house were changed, the optimum values of each parameter will change. Also, the optimum value of each parameter determined in this study was restricted by the selected options of each parameter (range and increment). For example, the optimum wall thickness corresponding to minimum life-cycle cost may be calculated to be 108mm; however, it is unrealistic to construct a RE wall with such precision (to the nearest millimetre). The increments for each parameter studied in this project were reasonable values in ranges recommended by experienced local builders.

In summary, each parameter in combination with the other parameters has different effects on the energy load and total life-cycle cost in different climates. It should be noted that the calculation of life-cycle cost is based on reverse cycle air conditioner only, and the result is sensitive to the type of heating/cooling system used. The effect of using other heating/cooling systems on the life-cycle cost will be different; however, this is beyond the scope of this study. The main contribution of this research is to provide recommendations for smart designs based on the relationship between each parameter and the energy load/life-cycle cost of a RE house. With the results presented in this study, designers and home owners will be able to make more informed decisions.

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Table 1 Characteristics of the base case house

Parameters	Descriptions
Floor area	96m^2 ($12m \times 8m$)
External wall height	2.7m
External wall thickness	330mm ($150mm\ RE + 30mm\ Insulation + 150mm\ RE$)
Cement stabilised rammed earth*	Thermal resistance (1m thick): 0.8m^2 K/W, heat capacity: 1940kJ/m^{3}K
Extruded polystyrene*	Thermal resistance (1m thick): 35.7m^2 K/W, heat capacity: 10.9kJ/m^{3}K
Concrete floor	100mm thick, R-Value=0.07m^{2}K/W
Ceiling	R 3.0 glass fibre batt + 10mm thick plasterboard
Pitched roof	R 1.0 glass fibre batt insulation + 1mm steel sheet
Window to wall ratio	10% for each direction
Window type	Single-glazed clear glass window with timber frame (50% openable, Overall Heat Transfer Coefficient=5.75W/m^{2}K, Solar Heat Gain Coefficient =0.69)
Window location	1.0m above floor, with a fixed window height of 1.5m
Window shading	Simple wooden frames + 1mm thick steel sheets

* The thermal properties of the material are selected as the default value from the software *AccuRate.*

Table 2 Details of three climate zones

	Climate zone 3	Climate zone 5	Climate zone 7
Climate type	Hot arid	Warm temperate	Cool temperate
Summer characteristics	Hot dry	Warm	Mild to warm
Winter characteristics	Warm	Cool	Cold
Summer temperature range (^{o}C)	22.5—36.7	16.6—28.6	10.6—24.2
Winter temperature range (^{o}C)	9.3—26.6	8.5—17.0	3.9—11.8
Typical city	Longreach	Adelaide	Ballarat
Heating thermostat settings (^{o}C)	20	20	20
Cooling thermostat settings (^{o}C)	27	25	23.5
6 star energy rating (MJ/m^2 per annum)	141(maximum)	96 (maximum)	197 (maximum)

Table 3 Values of parameters

Parameter	Value
Unit price of electricity for heating, P_H	0.31AUD/kWh
Unit price of electricity for cooling, P_C	0.35AUD/kWh
Heating coefficient of performance, E_H	3.7
Cooling energy efficiency rating, E_C	3.1
Interest rate, i	4.75%
Inflation rate, g	2.75%
Life time period, n	20 years (assuming that the reverse cycle air conditioner has a life time of 20 years)
Rammed earth walling	1133AUD/m^3
Extruded polystyrene	801AUD/m^3
Window	410AUD/m^2
Window eave	45AUD/m^2

Table 4 Effects of window size and shading on the costs (warm temperate climate)

Parameter	Running cost ($)	Initial cost ($)	Life-cycle cost ($)
East WWR (%)			
Base case	2890	43815	46704
20	2909(+1%)	43842(0%)	46752(0%)
30	3019(+4%)	43942(0%)	46961(+1%)
40	3187(+10%)	44261(+1%)	47448(+2%)
50	3349(+16%)	44834(+2%)	48183(+3%)
South WWR (%)			
Base case	2890	43815	46704
20	3115(+8%)	43899(0%)	47014(+1%)
30	3337(+15%)	43984(0%)	47321(+1%)
40	3634(+26%)	44216(+1%)	47850(+2%)
50	3930(+36%)	44376(+1%)	48306(+3%)
West WWR (%)			
Base case	2890	43815	46704
20	2926(+1%)	43842(0%)	46769(0%)
30	3011(+4%)	44087(+1%)	47098(+1%)
40	3183(+10%)	44492(+2%)	47675(+2%)
50	3353(+16%)	44513(+2%)	47866(+2%)
Projection factor			
Base case	2890	43815	46704
0.15	2929(+1%)	43863(0%)	46792(0%)
0.30	3093(+7%)	43985(0%)	47079(+1%)
0.45	3285(+14%)	43960(0%)	47246(+1%)
0.60	3507(+21%)	44233(1%)	47740(+2%)

"+" and "-" stand for increase and decrease, respectively.

Table 5 Effects of wall leaf and insulation thickness on the costs (warm temperate climate)

Parameter	Running cost ($)	Initial cost ($)	Life-cycle cost ($)
External wall thickness (mm)			
Base case	2890	43815	46704
175	2853(-1%)	46659(+6%)	49512(+6%)
200	2825(-2%)	49576(+13%)	52401(+12%)
225	2799(-3%)	52347(+19%)	55145(+18%)
Internal wall thickness (mm)			
Base case	2890	43815	46704
175	2835(-2%)	46732(+7%)	49567(+6%)
200	2805(-3%)	49431(+13%)	52236(+2%)
225	2769(-4%)	52347(+19%)	55116(+18%)
Insulation thickness (mm)			
Base case	2890	43815	46704
40	2550(-12%)	44842(+2%)	47392(+1%)
50	2318(-20%)	45571(+4%)	47889(+3%)
60	2180(-25%)	46227(+6%)	48407(+4%)
70	2074(-28%)	46889(+7%)	48964(+5%)
80	1972(-32%)	47764(+9%)	49736(+6%)
90	1910(-34%)	48498(+11%)	50407(+8%)
100	1862(-36%)	49233(+12%)	51094(+9%)

Table 6 Effects of window size on the costs (hot arid and cool temperate climates)

WWR (%)	Hot arid climates (Australian climate zone 3)			Cool temperate climates (Australian climate zone 7)		
	Running cost ($)	Initial cost ($)	Life-cycle cost ($)	Running cost ($)	Initial cost ($)	Life-cycle cost ($)

North window						
Base case	4270	46350	50620	9856	41989	51845
20	4654(+9%)	46220(0%)	50874(+1%)	9229(-6%)	42613(+1%)	51842(0%)
30	5201(+22%)	46199(0%)	51400(+2%)	8746(-11%)	42837(+1%)	51583(-1%)
40	5853(+37%)	46389(0%)	52242(+3%)	8385(-15%)	43290(+1%)	51675(0%)
50	6674(+56%)	46473(0%)	53147(+5%)	8163(-17%)	43374(+1%)	51537(-1%)
East window						
Base case	4270	46350	50620	9856	41989	51845
20	4687(+10%)	46449(0%)	51137(+1%)	9729(-1%)	42585(+1%)	52314(+1%)
30	5244(+23%)	46549(0%)	51793(+2%)	9637(-2%)	42728(+1%)	52365(+1%)
40	5863(+37%)	46541(0%)	52403(+4%)	9615(-2%)	43015(+1%)	52360(+2%)
50	6592(+54%)	46748(+1%)	53340(+5%)	9621(-2%)	43165(+1%)	52786(+2%)
South window						
Base case	4270	46350	50620	9856	41989	51845
20	4697(+10%)	46654(+1%)	51351(+1%)	10156(+3%)	42658(+1%)	52814(+2%)
30	5268(+23%)	46411(0%)	51679(+2%)	10446(+6%)	42837(+1%)	53282(+3%)
40	6007(+41%)	46823(+1%)	52829(+4%)	10757(+9%)	42970(+1%)	53726(+4%)
50	6717(+57%)	46580(0%)	53296(+5%)	11081(+12%)	43054(+1%)	54135(+4%)
West window						
Base case	4270	46350	50620	9856	41989	51845
20	4740(+11%)	46342(0%)	51082(+1%)	9761(-1%)	42501(+1%)	52262(+1%)
30	5292(+24%)	46549(0%)	51841(+2%)	9709(-1%)	42642(+1%)	52351(+1%)
40	5882(+38%)	47093(+2%)	52975(+5%)	9704(-2%)	43015(+1%)	52719(+2%)
50	6592(+54%)	47079(+2%)	53671(+6%)	9759(-1%)	43165(+1%)	52924(+2%)

Table 7 Effect of projection factor on the costs (hot arid and cool temperate climates)

Projection factor	Running cost ($)	Initial cost ($)	Life-cycle cost ($)
Hot arid climates (Australian climate zone 3)			
base case	4270	46350	50620

0.15	4155(-3%)	46323(-0%)	50478(-0%)
0.30	3963(-7%)	46297(-0%)	50260(-1%)
0.45	3752(-12%)	45110(-3%)	48861(-3%)
0.60	3594(-16%)	45280(-2%)	48874(-3%)
Cool temperate climates (Australian climate zone 7)			
base case	9856	41989	51845
0.15	10046(+2%)	42070(+0%)	52116(+1%)
0.30	10458(+6%)	42151(+0%)	52609(+1%)
0.45	10880(+10%)	42232(+1%)	53112(+2%)
0.60	11254(+14%)	42313(+1%)	53567(+3%)

Table 8 Effect of external wall thickness on costs (hot arid and cool temperate climates)

External wall thickness (mm)	Running cost ($)	Initial cost ($)	Life-cycle cost ($)
Hot arid climates (Australian climate zone 3)			
base case	4270	46350	50620
175	4256(0%)	49086(+6%)	53342(+5%)
200	4246(-1%)	51930(+12%)	56176(+11%)
225	4246(-1%)	54774(+18%)	59020(+17%)
Cool temperate climates (Australian climate zone 7)			
base case	9856	41989	51845
175	9801(-1%)	44811(+7%)	54612(+5%)
200	9739(-1%)	47655(+13%)	57394(+11%)
225	9683(-2%)	50500(+20%)	60183(+16%)

Table 9 Effect of internal wall thickness on costs (hot arid and cool temperate climates)

Internal wall thickness (mm)	Running cost ($)	Initial cost ($)	Life-cycle cost ($)
Hot arid climates (Australian climate zone 3)			

base case	4270	46350	50620
175	4270(0%)	49086(+6%)	53356(+5%)
200	4251(0%)	50736(+9%)	54987(+9%)
225	4256(0%)	53580(+16%)	57835(+14%)
Cool temperate climates (Australian climate zone 7)			
base case	9856	41989	51845
175	9775(-1%)	44811(+7%)	54587(+5%)
200	9709(-1%)	47655(+13%)	57365(+11%)
225	9635(-2%)	50500(+20%)	60134(+16%)

Table 10 Effect of insulation thickness on the costs (hot arid and cool temperate climates)

Insulation thickness (mm)	Running cost ($)	Initial cost ($)	Life-cycle cost ($)
Hot arid climates (Australian climate zone 3)			
base case	4270	46350	50620
40	4054(-5%)	45582(-2%)	49636(-2%)
50	3915(-8%)	46565(0%)	50480(0%)
60	3776(-12%)	47279(+2%)	51055(+1%)
70	3718(-13%)	48084(+4%)	51802(+2%)
80	3661(-14%)	48799(+5%)	52460(+4%)

90	3617(-15%)	49516(+7%)	53134(+5%)
100	3570(-16%)	50320(+9%)	53890(+6%)
Cool temperate climates (Australian climate zone 7)			
base case	9856	41989	51845
40	9116(-8%)	42732(+2%)	51848(+0%)
50	8618(-13%)	43501(+4%)	52119(+1%)
60	8256(-16%)	44289(+5%)	52546(+1%)
70	7989(-19%)	45079(+7%)	53068(+2%)
80	7780(-21%)	45869(+9%)	53649(+3%)
90	7607(-23%)	46661(+11%)	54268(+5%)
100	7464(-24%)	47465(+13%)	54929(+6%)

Figure 1 Calculation of projection factor. This figure illustrates how the projection factor is calculated. Projection factor is the ratio of the depth of window eave to the distance between the window sill and the bottom of window eave).

Figure 2 Increasing wall leaf thickness. This figure illustrates how this parameter is changed. When the thickness of one wall leaf increases, the thicknesses of the other wall leaf and the insulation are kept constant.

Figure 3 Increasing insulation thickness. This figure illustrates how this parameter is changed. When the thickness of insulation increases, the thicknesses of the rammed earth wall leaves are kept constant.

Figure 4 Basic model house. This figure shows the diagram of the basic model house, which provides the size and location of window in each wall and the length and width of the model house.

Figure 5 Selected cities in different climate zones. This figure shows the location of the three cities investigated in this study, namely Longreach, Adelaide and Ballarat.

Figure 6 Relationships between heating and cooling capacity and the price of air conditioner. The figure shows that the price of air conditioner reflects the machine's capacity to cool or heat. Symbol ◆ and ▲ presented in this figure stand for heating and cooling respectively.

Figure 7 Effect of window size on heating and cooling loads (warm temperate climate). This figure illustrates the relationship between each window size and the heating/cooling load of the base case house in a warm temperature climate (such as Australian climate zone 5). Symbol ■ and ■ presented in this figure stand for heating and cooling respectively.

Figure 8 Effect of window shading on heating and cooling loads (warm temperate climate). This figure illustrates the relationship between window shading (projection factor) and the heating/cooling load of the base case house in a warm temperature climate (such as Australian climate zone 5). Symbol ▫ and ▪ presented in this figure stand for heating and cooling respectively.

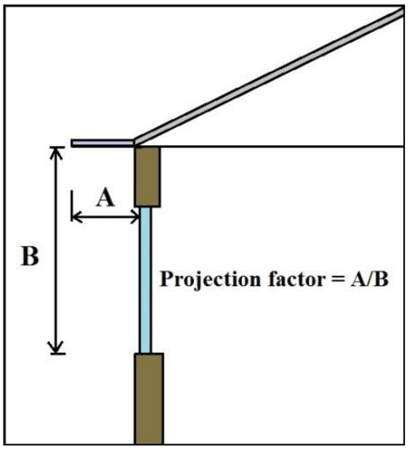
Figure 9 Effect of wall leaf thickness on heating and cooling loads (warm temperate climate). This figure illustrates the relationship between each rammed earth wall leaf thickness and the heating/cooling load of the base case house in a warm temperature climate (such as Australian climate zone 5). Symbol ▫ and ▪ presented in this figure stand for heating and cooling respectively.

Figure 10 Effect of insulation thickness on heating and cooling loads (warm temperate climate). This figure illustrates the relationship between insulation thickness and the heating/cooling load of the base case house in a warm temperature climate (such as Australian climate zone 5). Symbol ▫ and ▪ presented in this figure stand for heating and cooling respectively.

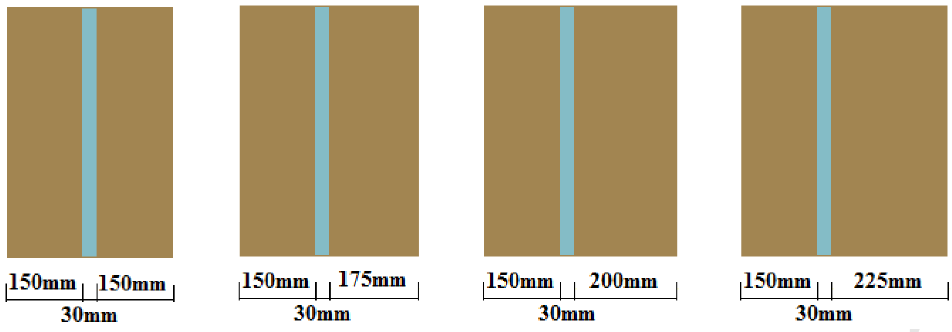
Figure 11 Effect of each parameter on the total energy load (hot arid and cool temperate climates). This figure illustrates the influence of each parameter on the total energy load of the base case house in a hot arid (such as Australian climate zone 3) and cool temperate climate (such as Australian climate zone 7). Symbol ■ and ◆ presented in this figure stand for hot arid climate and cool temperate climate respectively.

Figure 12 Effect of north window size on the costs (warm temperate climates). This figure shows the relationship between north window size and the running cost/initial cost/total life-cycle cost of the base case house in a warm temperate climate (such as Australian climate zone 5). Symbol ■, ■ and ■ presented in this figure stand for running cost, initial cost and total life-cycle cost respectively.

Figure(1)



Figure(2)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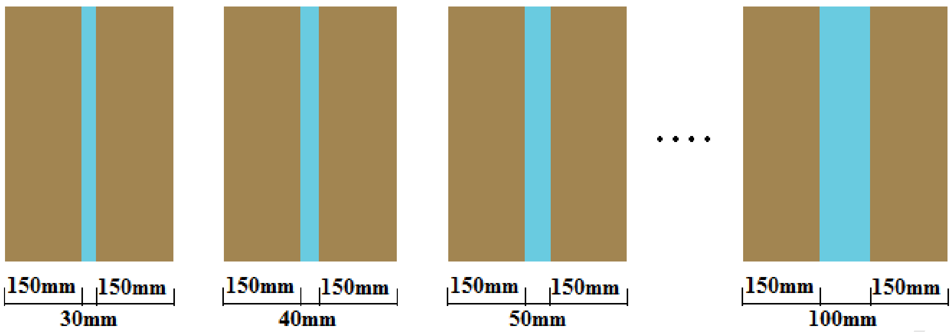
Figure(3)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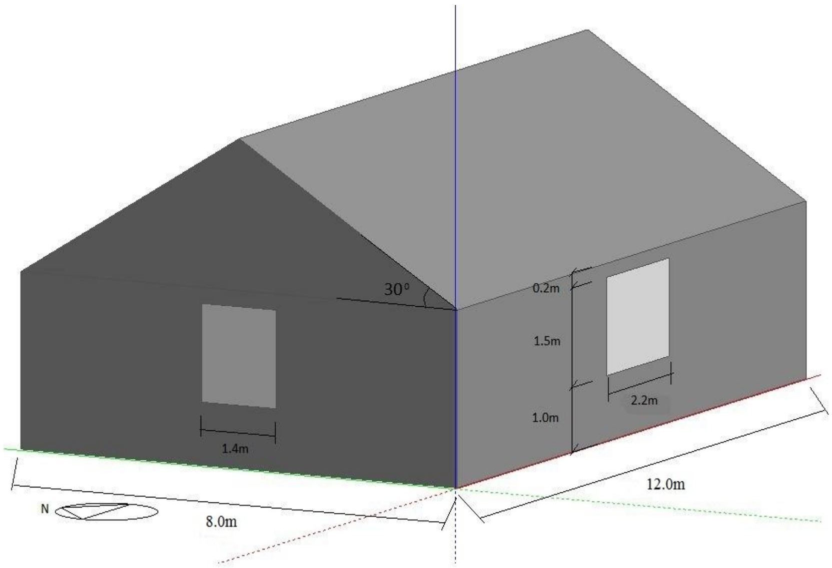
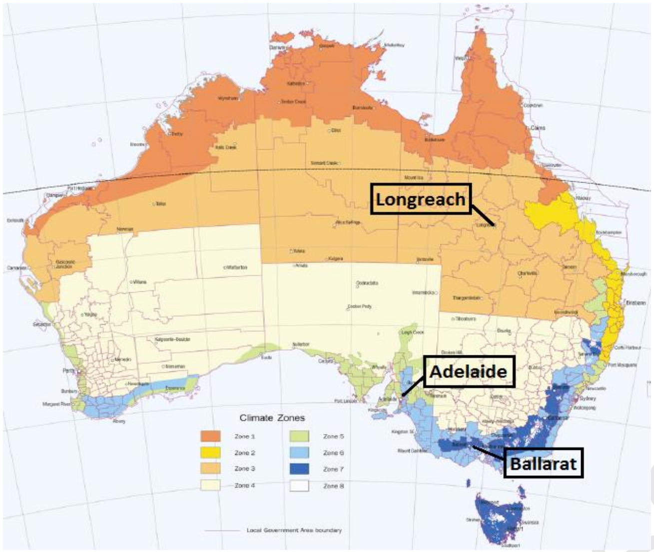
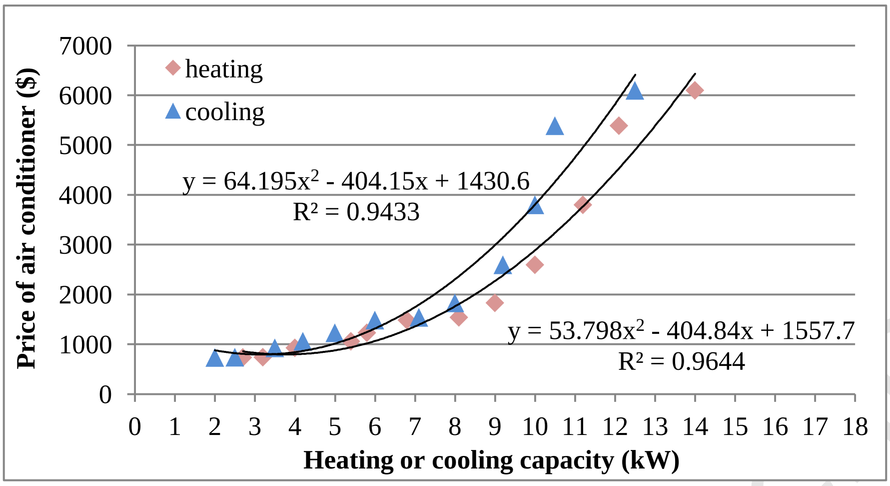
Figure(4)



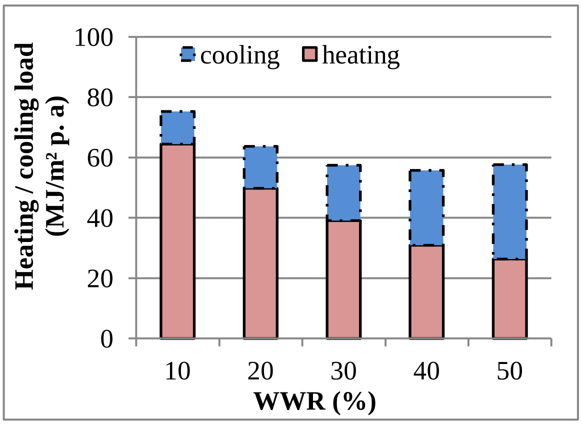
Figure(5)


Longreach
Adelaide
Ballarat
Climate Zones
Zone 1
Zone 2
Zone 3
Zone 4
Zone 5
Zone 6
Zone 7
Zone 8
Local Government Area boundary

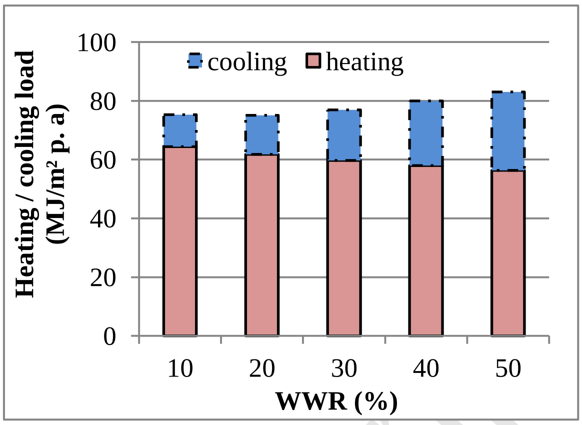


Price of air conditioner ($)
7000
6000
5000
4000
3000
2000
1000
0
heating
cooling
y = 64.195x² - 404.15x + 1430.6
R² = 0.9433
y = 53.798x² - 404.84x + 1557.7
R² = 0.9644
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Heating or cooling capacity (kW)

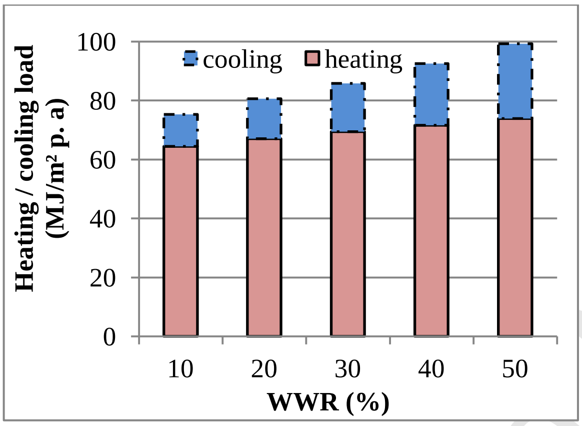
Figure 7



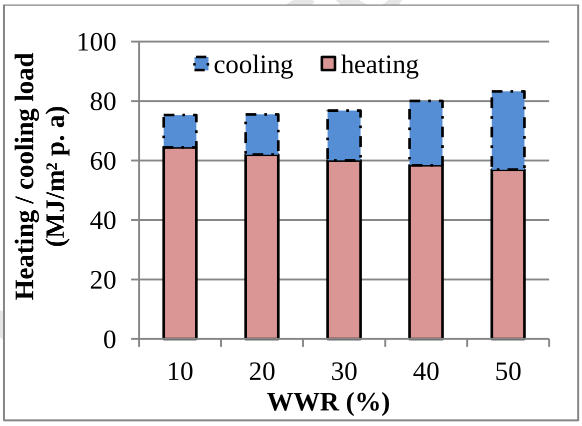
(a) North window



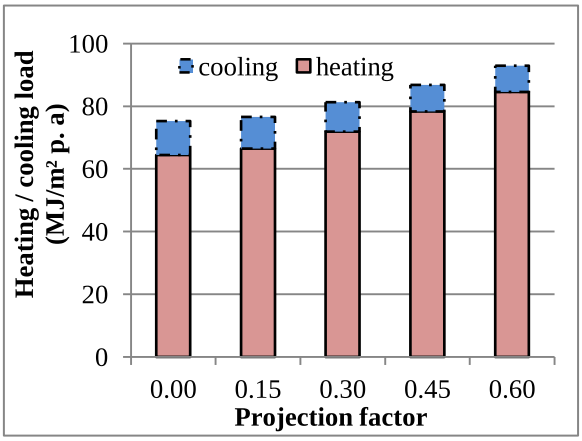
(b) East window

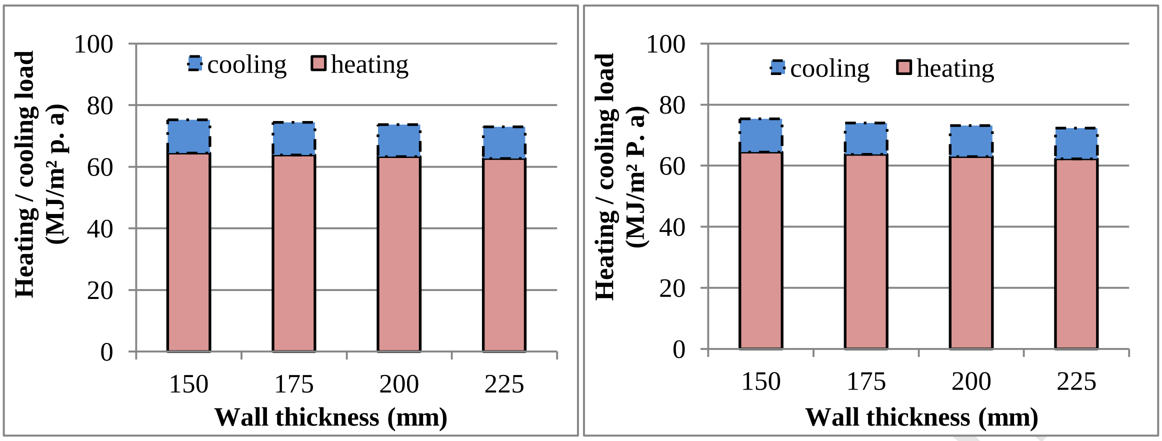


(c) South window

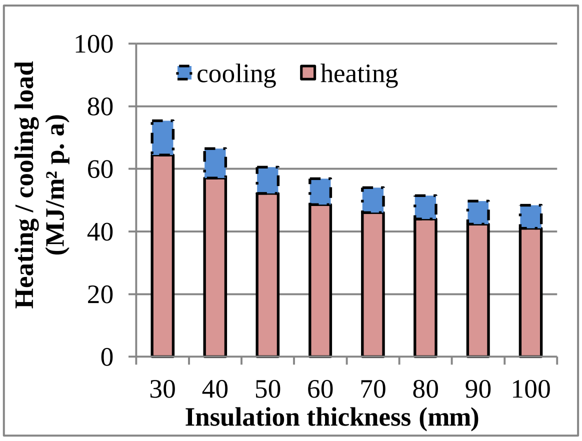


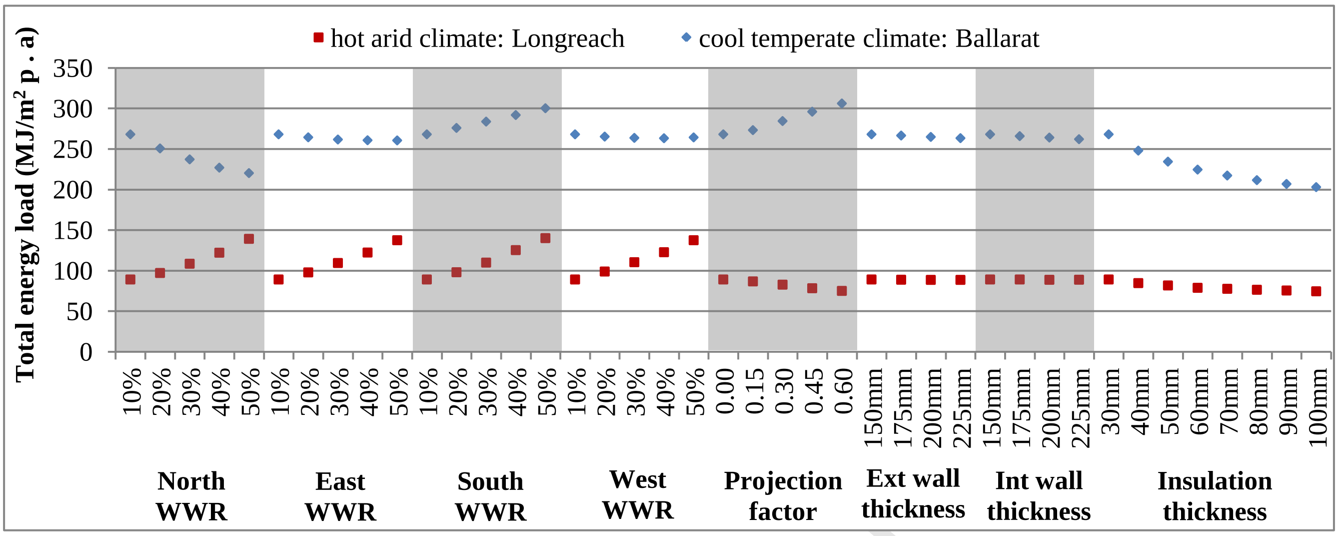
(d) West window

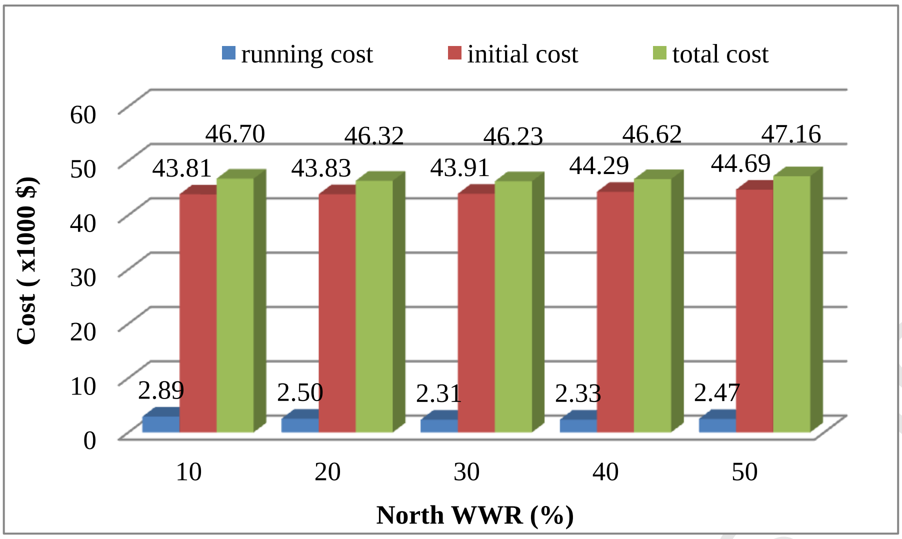

100
80
60
40
20
0
cooling
heating
Heating / cooling load
(MJ/m² p. a)
0.00
0.15
0.30
0.45
0.60
Projection factor



(a) External wall (b) Internal wall


100
80
60
40
20
0
cooling
heating
Heating / cooling load
(MJ/m² p. a)
30
40
50
60
70
80
90
100
Insulation thickness (mm)


hot arid climate: Longreach
cool temperate climate: Ballarat
Total energy load (MJ/m2 p . a)
350
300
250
200
150
100
50
0
10% 20% 30% 40% 50%
0.00 0.15 0.30 0.45 0.60
150mm 175mm 200mm 225mm
30mm 40mm 50mm 60mm 70mm 80mm 90mm 100mm
North WWR
East WWR
South WWR
West WWR
Projection factor
Ext wall thickness
Int wall thickness
Insulation thickness


running cost
initial cost
total cost
Cost (x1000 $)
60
50
40
30
20
10
0
46.70
46.32
46.23
46.62
47.16
43.81
43.83
43.91
44.29
44.69
2.89
2.50
2.31
2.33
2.47
10
20
30
40
50
North WWR (%)