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Towards Passive Design Strategies for Improving Thermal Comfort Performance in a Naturally Ventilated Residence

Kritika Rana

School of Architecture, Design and Planning, University of Sydney, Darlington, NSW 2008, Australia
Department of Architecture and Urban Planning, Institute of Engineering, Tribhuvan University,
Lalitpur 44600, Nepal

*Corresponding author: r.kritika@live.com

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Passive design integrates a wide range of climate-based strategies to increase occupant thermal comfort and minimise the need for mechanical systems for heating and cooling. The aim of this study was to improve the thermal comfort performance in a naturally ventilated residence through the identification and evaluation of the best set of passive design strategies. A two-storey residence located in Washington, United States with a temperate climate was selected as the case study residence. A reference simulation model was developed by replicating only the orientation and massing of the case study residence, while certain assumptions were made for other building characteristics. Thermal comfort performance analysis was conducted in the DesignBuilder software. A set of design strategies were introduced as interventions followed by simulation runs to efficiently track progress. From the reference simulation model to the final intervention model, a 50% reduction in the annual discomfort hours was anticipated in the five selected zones of the residence. Following the integration of four major interventions, the target discomfort hours were met in three zones—library, bedroom 1 and bedroom 2, with 53.03%, 60.42% and 58.94% reduction in discomfort hours, respectively. The two remaining zones—living and lounge also had a notable improvement with a reduction of 43.93% and 45.99%, respectively. The successful design strategies included—incorporation of triple glazed, low-emissivity and argon filled openings with wooden frames; integration of overhangs in south-facing windows, minor reduction of openings in the east and west façade, and addition of blinds for window shading; and use of an energy code standard construction for the building components and further addition of insulation in the building envelope. The most effective intervention was the customisation of the window operation schedule based on seasonal air temperature differences to optimise natural ventilation. This study demonstrated that occupant thermal comfort can be significantly improved throughout the year with the appropriate use of passive heating and cooling strategies, thereby reducing energy consumption and the environmental impact of buildings.

Keywords: thermal comfort performance, natural ventilation, building simulation, sustainability, passive design strategies.



Introduction

With the alarming increase in energy consumption worldwide, the building and construction industry is one of the essential sectors to address the challenges arising due to global climate change (De la Cruz-Lovera et al., 2017). One of the most energy-intensive sectors, buildings account for over 40% of the global energy consumption and about one-third of the global greenhouse gas emissions (Khakian et al., 2020). More importantly, residential building sector represents around 25% of the global energy demand and 17% of the greenhouse gas emissions. In light of these concerns, there has been growing research into reducing energy consumption and greenhouse gas emissions, particularly in the residential building sector. In recent years, the importance of developing sustainable, passive, green, energy-efficient or net zero energy buildings to address the grave challenge of global climate change is also gaining momentum.

Green buildings, in particular, focus on improving the energy efficiency of the building and on mitigating its negative impacts on the natural resources and the environment (Zhang et al., 2019). Moreover, green building strategies aim to reduce the negative impacts on energy, water, materials, and other natural resources across all life cycle stages of the building from siting to design, construction, operation, maintenance, renovation, and demolition (Vatalis et al., 2013, Zhang et al., 2019). With the increasing awareness in the need of green buildings, over 600 rating tools have been developed and are promoted across the globe as a guideline for green building development (Illankoon et al., 2019, Poveda and Young, 2015). Building Research Establishment Environmental Assessment Method (BREEAM) was launched in the United Kingdom as the first rating tool, while Leadership in Energy and Environmental Design (LEED) introduced by the United States Green Building Council (USGBC) is the most widely used rating tool (Illankoon et al., 2019, Khan et al., 2019). Other frequently used certification standards include Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) in Japan, Green Star in Australia, and Green Mark in Singapore (Khan et al., 2021, Illankoon et al., 2019). Energy use is one of the major elements examined in the assessment process of these rating tools, and the primary approach to reducing energy use is improving energy efficiency (Chen et al., 2015, Yu et al., 2020).

Building energy efficiency can be enhanced largely through active and/or passive strategies (Li et al., 2017). Active strategies focus on the use of energy-efficient building service systems including heating, ventilation and air conditioning (HVAC) systems, lighting, and hot water system, to reduce energy consumption (Chen et al., 2015). Alternatively, passive design strategies aim to harness the internal environment conditions to reduce the energy demand by utilising energy-efficient building design elements such as the form, layout, and building envelope as opposed to mechanical systems (Yu et al., 2020). As compared to active strategies, passive design strategies are associated with longer life spans, lower life cycle costs, and higher benefits in energy saving (Dahlstrøm et al., 2012, Yu et al., 2020). Due to the proven effectiveness of passive design strategies in energy savings, the passive design approach has also been recognised in many green building rating tools including BREEAM, LEED, and CASBEE (Chen et al., 2015). Similarly, the Passive House Standard is a widely used passive building design tool which was developed by the Passive House Institute in Germany (Moreno-Rangel, 2021). The Passive House Standard provides certification to those buildings that comply with its strict design and energy performance criteria (Moreno-Rangel et al., 2020). Moreover, the Passive House concept promotes the passive design approach by enhancing thermal comfort conditions at minimum energy expenditure (Fernandez-Antolin et al., 2019).

In residential buildings, the largest proportion of the energy demand is shared by the HVAC systems that aim to provide occupant thermal comfort. Alarmingly, about 32% of the total energy consumption in residential buildings worldwide is attributed to heating alone (Ürge-Vorsatz et al., 2015). Passive design strategies aim to utilise natural energy sources in the building such as the solar heat energy and wind energy to minimise the need for mechanical systems for heating

and cooling (Zahiri and Altan, 2016). Responding to local climate, passive design approaches also focus on the building design and the thermal performance of building envelope and construction elements, to reduce energy demand and increase occupant thermal comfort. The building envelope, comprising of walls, roofs, insulation materials, fenestration, and shading devices, has a significant impact on daylighting, thermal comfort, indoor environmental quality, as well as the energy consumption of HVAC systems (Yu et al., 2020). Sustainable and bioclimatic architecture represents an alternative building construction method, which considers the local climate conditions and integrates passive solar technologies, or heating and cooling techniques to passively absorb or protect from the sun's energy (Manzano-Agugliaro et al., 2015). Sustainable and passive design include a wide range of strategies revolving around the building orientation and form, interior layout of spaces, and site planning as per the sun path and wind flow; air movement, and position and protection of openings; and optimisation of the building envelope including selection of appropriate construction materials and specifications for the walls, floor and roof (Anna-Maria, 2009). With the help of passive design strategies, the reliance on mechanical systems to achieve thermal comfort can be minimised to a large extent.

As people generally spend over 80% of their lives in buildings, indoor thermal performance has a major impact on their overall health and wellbeing as well as their quality of life (Manzano-Agugliaro et al., 2015). Defined as the feeling of neither warm or cold, thermal comfort is influenced by several parameters including indoor air temperature, radiant temperature, relative humidity and air movement (Majewski et al., 2020). Natural ventilation is one of the fundamental passive design strategies, particularly for cooling-dominated climates, and it plays an essential role in providing occupants with a healthy indoor environment and acceptable thermal comfort conditions (Omrani et al., 2017). Moreover, naturally ventilated buildings consume 30-40% less energy than mechanically ventilated buildings. The benefits of natural ventilation have led to its increased use in a wide range of settings including residential and commercial. However, there are several challenges when using natural ventilation for indoor thermal comfort such as difficulty to predict uncertainties arising due to variable meteorological conditions and inability to control occupant behaviour on windows operation (Moret Rodrigues et al., 2019). The effective application of natural ventilation for thermal comfort is also reliant on the season and climate. Natural ventilation may be used as an effective and efficient cooling strategy during the summer and warmer months yet can be detrimental to thermal comfort in winter and colder months. Similarly, natural ventilation may be a particularly useful strategy to maintain thermal comfort in a cooling-dominant climate as compared to heating-dominant climate. In a temperate climate with warm summers and cool winters, natural ventilation is only one of the potential strategies to improve indoor thermal comfort.

The extent to which a wide range of passive design strategies aid in enhancing thermal comfort performance in a naturally ventilated residence with no active systems for heating or cooling is an emerging and essential topic for research. Moreover, the highly advanced building simulation software such as DesignBuilder provides an ideal platform for thermal comfort performance analysis. Nonetheless, majority of the prior studies that have used DesignBuilder as a building simulation tool are mainly focused on building energy simulation and analysis (Rey-Hernández et al., 2018, Cárdenas et al., 2016, Balbis-Morejón et al., 2021). Similarly, there are a number of previous studies that have used DesignBuilder to explore the effectiveness of passive design strategies in reducing building energy demand and consumption (Wang et al., 2016, Fernandez-Antolin et al., 2019, Vargas and Hamui, 2021). However, research suggests that rather than crediting the success of passive design strategies to reduction in energy demand, it is essential to assess thermal comfort performance in passively designed buildings (Wang et al., 2014, Chen et al., 2015). While a few studies have utilised DesignBuilder to assess thermal comfort performance, these studies primarily investigate the effectiveness of a single intervention (Al-Absi et al., 2021, Mabdeh et al., 2021). Although prior studies have demonstrated the effectiveness of natural ventilation on both

energy reduction and thermal comfort, the need of other passive design strategies in a naturally ventilated building requires further investigation (Raji et al., 2020, Oropeza Pérez, 2015). Similarly, research suggests that the effectiveness of passive design strategies can differ as per the individual room's thermal characteristics, which emphasises the need to investigate thermal comfort in a room-to-room basis rather than the building as a whole (Wang et al., 2014).

In light of these findings, it is essential to conduct a thermal comfort performance analysis to assess the effectiveness of passive design strategies. Especially in a naturally ventilated residence without any active HVAC systems, the role of passive design strategies in enhancing thermal comfort is not widely understood. Therefore, the aim of this study was to improve the thermal comfort performance in a naturally ventilated residence through the identification and evaluation of the best set of passive design strategies. Building simulation through DesignBuilder provides an ideal platform to test various passive design strategies and identify the ideal strategies that are positively associated with improvement in thermal comfort for the particular climate. Moreover, it will also provide an opportunity to explore and compare the effectiveness of these strategies on each thermal zone within the building. Therefore, the findings of this study will reinforce the importance of passive design strategies which will be evidenced by the extent to which each strategy contributed to the improvement in thermal comfort. This study will provide a reference for the design and construction of residential buildings integrating passive design strategies in a temperate climate. Furthermore, this study will also demonstrate how occupant thermal comfort can be significantly improved throughout the year with the appropriate use of passive heating and cooling strategies, thereby reducing energy consumption and the environmental impact of buildings.

Firstly, this paper will present the selected case study residence, which is a sustainable and energy efficient residence that employs natural ventilation. The climate responsive passive design strategies integrated in the residence in order to achieve occupant comfort in all seasons will be outlined. Secondly, a reference simulation model will be developed by replicating only the orientation and massing of the case study residence, while certain assumptions will be made for other building characteristics. An annual simulation will be performed in DesignBuilder software, on the basis of which thermal comfort performance analysis will be conducted. The potential design strategies to improve the thermal comfort performance in the particular climate will also be identified. Finally, integrating the best set of design strategies as interventions in the reference simulation model, this study will endeavour to improve the thermal comfort performance of the naturally ventilated residence. The improvement will also be evidenced by simulation results and thermal comfort performance analysis following the integration of each intervention, as well as comparison of the reference simulation model and final intervention model.

Description of Selected Case Study Residence

For the purpose of this study, a two-storey residential building located in Bainbridge Island, Washington, United States, which employs natural ventilation was selected as the case study residence. Being a sustainable and energy-efficient residence that has achieved LEED Platinum certification, adequate information, images as well as architectural drawings were readily available through online platforms. A description of the selected case study residence extracted from the secondary data sources are summarised in the following paragraphs.

The residence was conceived as per the owner's vision of a contemporary residence integrating sustainability and energy efficiency at its finest, such that it would become a milestone (ArchDaily, 2011). Completed in 2010, the residence was established as the first LEED Platinum certified residence in Washington State outside the city of Seattle. The climate of Bainbridge Island is warm and temperate, with an average temperature of 10.6 °C and an average rainfall of 1274 mm, with rainfall more prominent in winter compared to summer (Climate-Data, 2021a).

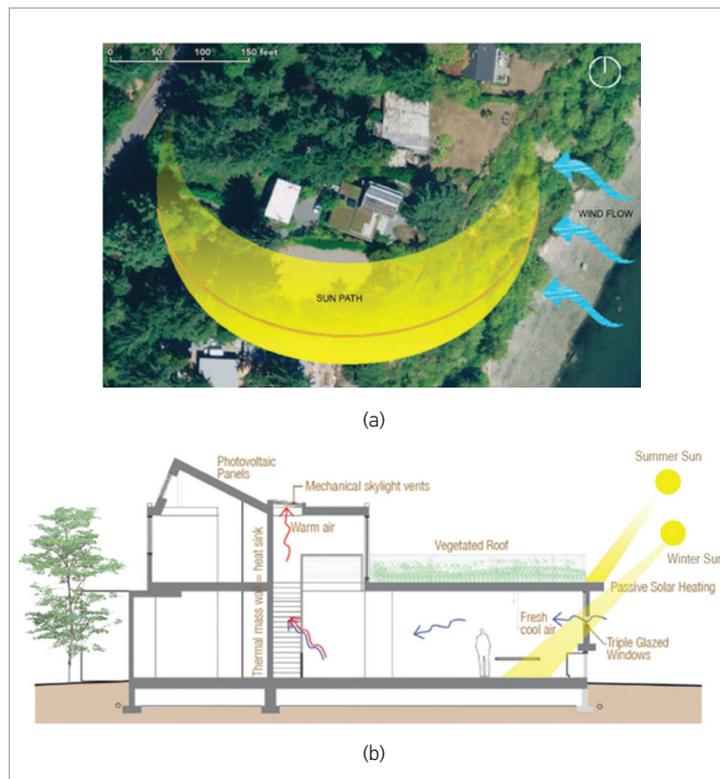
Materials and Methods

The residence incorporates a myriad of sustainable design practices as per the climate. In particular, the integration of passive heating and cooling mechanisms was a major consideration during the residence design (Solaripedia, 2011). The east-west orientation of the residence on the site maximises the potential of sunlight and wind penetration (Fig. 1a). A central thermal mass core of concrete masonry unit (CMU) spine runs through the east to west of the residence, strategically dividing the public and private spaces at the same time. The two-storey thermal mass wall functions as a heat sink during summer and heat source during winter to ensure that the temperature remains constant throughout the residence. The orientation and fenestration of openings function well to achieve thermal comfort for the occupants. Large east and south openings along the sun path allow maximum penetration of the sunlight especially during cold winters, and the windows are triple-glazed to avoid any heat loss (World-Architects, 2011). The thermal mass walls and the concrete floors store the heat, which is circulated throughout the house as the temperature falls down. Along with the windows, mechanical skylight vents placed strategically at the centre of the

residence adjacent to the thermal mass walls function as a source of daylight and natural ventilation. Especially because of the close proximity of a water body towards the east of the residence, cool drafts entering through the east facing windows circulate fresh air throughout the residence as an effective cooling mechanism during hot summers. The overall design of a double height core along the thermal mass walls accompanied by mechanical vents generates a stack effect for the residence to naturally ventilate during summer and passively heat during winter (Fig. 1b).

Fig. 1

Case study residence
(a) Sun path and wind direction. Adapted from Maps-Apple. (b) Demonstration of passive design strategies. Adapted from ArchDaily (2011)



A wide range of energy efficient mechanisms, along with the passive design strategies and use of sustainable construction materials have reduced the energy consumption of the residence by 70% in comparison with an average North American residence (ArchDaily, 2011). Approximately 40% of the energy demand is met through the photovoltaic collectors placed on the rooftop, and the two solar thermal collectors that supply hot water (Solaripedia, 2011). The roof of the residence features a vegetated garden patio planted with pre-grown drought resistant sedums, and rainwater is collected from the 100% of the roof area, understanding the vital role of rainwater collection in a rainy climate. The construction materials used in the residence was a result of careful selection of locally sourced and sustainable materials. A pre-existing cabin on the site was deconstructed and 98% of the building materials were diverted and reused from the landfill (Solaripedia, 2011). All the innovative design strategies function together to establish the residence as an epitome of sustainability and energy efficiency.

Development of a Reference Simulation Model for Thermal Comfort Analysis

Differences between the case study residence and the reference simulation model

As described previously, the aim of this study was to improve the thermal comfort performance in a naturally ventilated residence. To achieve this, a wide range of passive design strategies will be introduced, and the improvement will be measured through thermal comfort performance analysis. In order to successfully measure the extent to which each strategy led to an improvement, a base model or a reference simulation model is essential. The purpose of the selected case study residence was to serve as a reference, while developing the reference simulation model. Further, adequate information as well as architectural drawings of the case study residence was readily available in online platforms, on the basis of which, the reference simulation model could be developed.

However, the case study residence is already an excellent example of a sustainable and energy efficient residence. The residence has achieved LEED Platinum certification, the highest certification in green building design, which indicates that there is little to no room for improvement. This is attributed to the adoption of bioclimatic design for the orientation and massing of the building, use of sustainable construction materials, and implementation of energy efficient mechanisms and technologies. Therefore, for the purpose of this study, only the orientation and massing of the case study residence were replicated to produce the reference simulation model. To be specific, the overall dimension, orientation and interior layout of the reference simulation model and case study residence would be identical, and these factors would not be altered when design strategies are introduced. This design control would allow comparisons to be made and efficiently track the improvement in the reference model attributed to the introduction of the strategy. Moreover, the orientation and massing of the reference model would already be ideal for the climate as these are based on the bioclimatic design principles used in the case study residence.

Apart from the orientation and massing, other building characteristics of the reference simulation model will not be based on the case study residence. Certain assumptions will be made for the construction materials as well as the specification of openings as outlined in detail in the subsequent sections. This will help identify the extent to which alternatives based on passive design strategies lead to improvement in thermal comfort performance. Further, thermal comfort analysis will only be conducted in five thermal zones within the residence based on the occupancy hours of each zone. In energy analysis, generally the energy used by the entire building is calculated. However, thermal comfort performance in each thermal zone within the building is different, therefore, it is essential to take each zone separately and perform thermal comfort analysis based on the occupancy hours for the particular zone.

It is also essential to highlight that the passive design strategies introduced as interventions will aim to improve the thermal comfort performance in the selected thermal zones. As such, these interventions will not aim to replicate the construction materials, openings specifications, and other technologies used in the original LEED Platinum certified case study residence. This study will also not seek to identify or evaluate the strategies used that led to the platinum certification by the case study residence. Nonetheless, the case study residence presents an opportunity to develop a suitable reference simulation model, where the effectiveness and impact of a wide range of passive design strategies on thermal comfort performance can be compared and analysed.

Use of DesignBuilder as the simulation tool

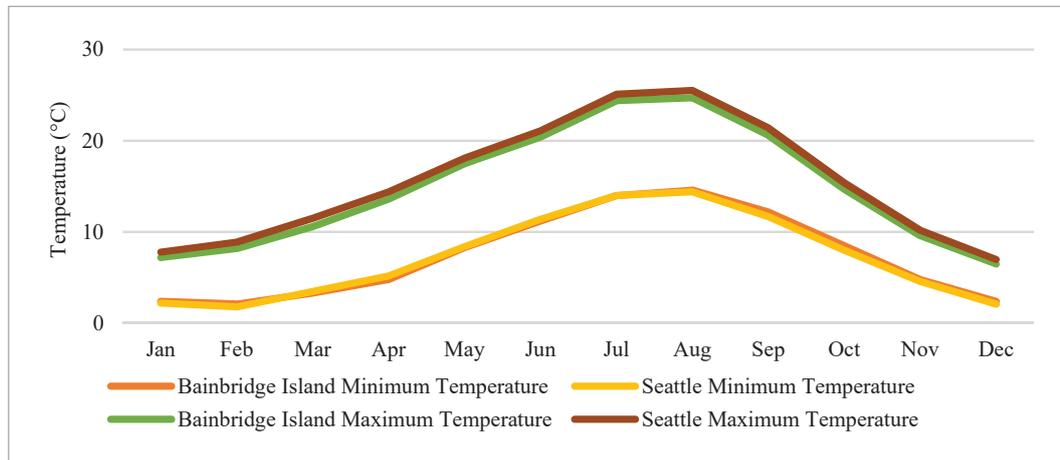
In this study, the analysis of thermal comfort performance was conducted using DesignBuilder software. DesignBuilder is a frequently used tool to assess energy efficiency and occupant thermal comfort in buildings. It uses EnergyPlus for building energy simulations, which is a whole-building simulation engine developed by the US Department of Energy. Integrating heat and mass balance calculations, EnergyPlus has shown to accurately predict temperatures in naturally ventilated spaces (DesignBuilder Software Australia, 2021).

Location and weather data used in DesignBuilder

The weather data for Bainbridge Island was not available in EnergyPlus weather format for use in DesignBuilder. Therefore, the weather data for Seattle-Tacoma International Airport, Washington, United States, which lies in its close proximity was taken as a reference. High similarities can be observed between the weather data of the two locations (Climate-Data, 2021a, Climate-Data, 2021b). Fig. 2 illustrates the comparison between minimum and maximum temperatures of Bainbridge Island and Seattle-Tacoma International Airport. Simulation weather data for Seattle-Tacoma International Airport was obtained from EnergyPlus (2021).

Fig. 2

Comparison between temperatures of Bainbridge Island and Seattle-Tacoma International Airport. Source: Climate-Data (2021a), Climate-Data (2021b)

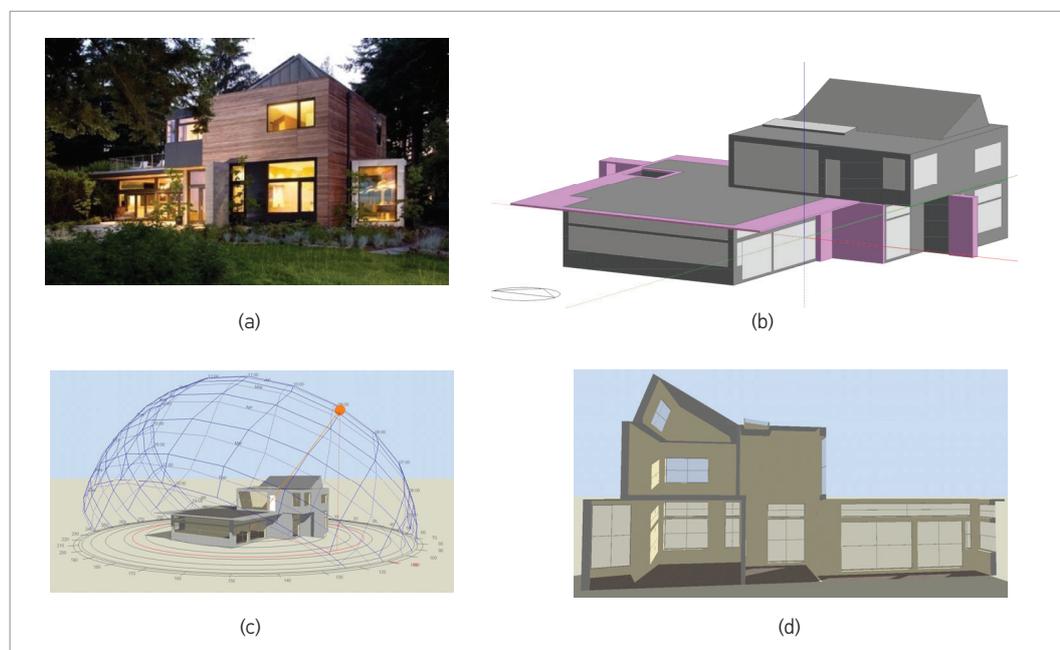


Development of the reference simulation model

Referring to the case study residence, the reference simulation model was developed in DesignBuilder (Fig. 3). In the reference model, only the orientation and massing of the case study residence were replicated. Therefore, the built form, interior layout, and openings dimensions were preserved according to that of the case study residence.

Fig. 3

Case study residence
 (a) Original building.
 Source: ArchDaily (2011)
 (b) Reference simulation model in DesignBuilder
 (c) 3D model visualisation
 (d) Sectional diagram



The interior spaces in the case study residence were categorised according to function: day spaces—living spaces and recreational areas; night spaces—bedrooms; and other spaces—ancillary spaces and circulation area (Fig. 4). The design was simplified for representation in DesignBuilder by combining thermally similar zones to reduce the number of zones. Virtual partitions were added to define zones in spaces with no enclosing walls. The kitchen, dining and living room were combined into one zone and enclosed with a virtual partition. Ensuite and changing rooms were combined with the bedrooms in both floors. Although the circulation and bathroom zones were also combined, these will not be accounted in the analysis of thermal performance. The reference simulation model comprised of five major thermal zones to be accounted for the thermal performance analysis. Daytime use zones were the living room and library in ground floor and the lounge in first floor, and night-time use zones were the two bedrooms in the ground and first floor (Table 1). The total occupied floor area was 304.7 m².

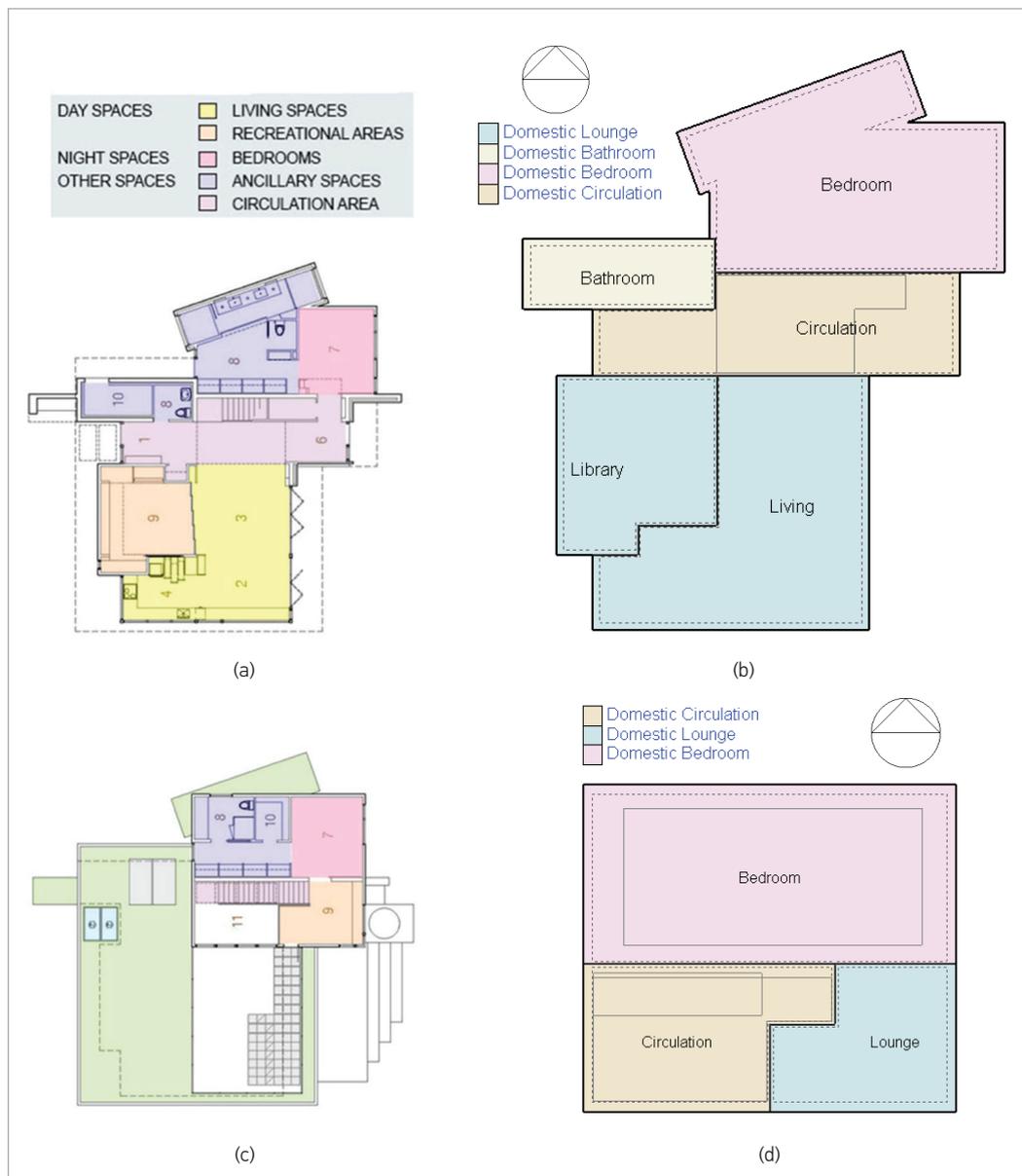


Fig. 4

Case study residence floor plans (a) Original ground floor plan. (b) Ground floor plan in DesignBuilder. (c) Original first floor plan. (d) First floor plan in DesignBuilder. Original plans adapted from ArchDaily (2011)

The reference simulation model followed specific guidelines such that it would serve as a reference model, which would not be altered when interventions are introduced so that improvements could be tracked effectively. For this purpose, specific DesignBuilder templates that are databases of typical generic data were loaded either for the entire model or for each zone. For the reference model, the HVAC template was selected as natural ventilation without any heating or cooling systems. The operation schedule of natural ventilation was selected as “on 24/7” and the model was set to calculate natural ventilation. For the reference model, other internal loads such as general lighting was turned on, while equipment and computers were turned off. Similarly, from the activity templates available for residential spaces in DesignBuilder, a specific template was selected for each zone (Table 1). The occupancy density and metabolic activity for each zone was also based on the selected activity template.

Table 1

Characteristics of each zone and the use of DesignBuilder templates in the reference simulation model

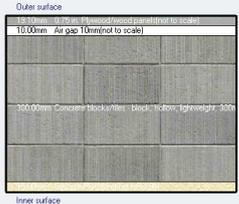
	Day Zones			Night Zones	
	Library	Living	Lounge	Bedroom 1	Bedroom 2
Floor	Ground	Ground	First	Ground	First
Floor area (m ²)	33.20	63.12	16.51	64.58	51.05
Activity template	Domestic Lounge	Domestic Lounge	Domestic Lounge	Domestic Bedroom	Domestic Bedroom
Occupancy density (people/m ²)	0.0188	0.0188	0.0188	0.0229	0.0229
Metabolic activity	Eating/ Drinking	Eating/ Drinking	Eating/ Drinking	Bedroom/ Dwelling	Bedroom/ Dwelling

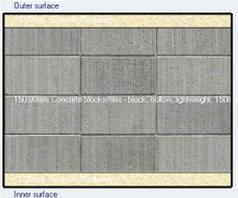
Construction materials in the reference simulation model

The majority of construction materials used in the reference simulation model were as specified in the case study residence. However, all construction systems were assumed to be uninsulated, and the specifications of construction materials differs widely as the aim was not to replicate the construction systems of the case study residence. The specification of construction materials used in the reference simulation model are shown in Table 2. In terms of wall and roof projections, these were modelled as components with the construction system selected as lightweight cast concrete.

Table 2

Specifications of construction materials in the reference simulation model

Construction Materials Specification	Schematic Diagram
<p>External Wall: Uninsulated brick/block</p> <ul style="list-style-type: none"> _ 19mm plywood/wood panels _ 10mm air gap _ 300mm lightweight hollow concrete block _ 15mm gypsum plastering _ R-value (m²K/W): 0.943 _ U-value (W/m²K): 1.060 	
<p>Ground/Internal Floor: Uninsulated medium weight floor</p> <ul style="list-style-type: none"> _ 30mm timber flooring _ 70mm screed _ 100mm cast concrete _ R-value (m²K/W): 0.684 _ U-value (W/m²K): 1.463 	

Construction Materials Specification	Schematic Diagram
<p>Internal Partitions: Hollow concrete block</p> <ul style="list-style-type: none"> _ 15mm gypsum plastering _ 150mm lightweight hollow concrete blocks _ 15mm gypsum plastering _ R-value ($\text{m}^2\text{K}/\text{W}$): 0.648 _ U-value ($\text{W}/\text{m}^2\text{K}$): 1.544 	
<p>Flat Roof: Uninsulated medium weight flat roof</p> <ul style="list-style-type: none"> _ 19mm asphalt _ 13mm fibreboard _ 100mm lightweight cast concrete _ R-value ($\text{m}^2\text{K}/\text{W}$): 0.647 _ U-value ($\text{W}/\text{m}^2\text{K}$): 1.546 	
<p>Pitched Roof: Metal roof</p> <ul style="list-style-type: none"> _ 15mm lightweight metallic cladding _ 50mm metal deck _ R-value ($\text{m}^2\text{K}/\text{W}$): 1.754 _ U-value ($\text{W}/\text{m}^2\text{K}$): 0.570 	

Specification of openings in the reference simulation model

The windows and doors dimensions in the reference simulation model were as per the openings schedule of the case study residence. However, the glazing type of all windows and glass doors were assumed to be single glazed 6mm clear glass, with U-value = $5.8 \text{ W}/\text{m}^2\text{K}$, solar heat gain coefficient (SHGC) = 0.86 and visible light transmittance (VLT) = 0.88. The construction of frames was assumed to be aluminium window frame. The operation schedule of all windows was assumed to be on 24/7. The glass doors were modelled as windows with the same assumptions. However, the operation schedule of all doors was assumed to be off 24/7. For free aperture, the opening position was from the bottom, and the percentage of glazing area that opens was 50%.

Methodology for Analysis of Thermal Comfort

Criteria for assessing thermal comfort

According to the various bioclimatic diagrams used as tools to determine comfort levels, Manzano-Agugliaro et al. (2015) suggests that the commonly used parameters to determine thermal comfort include mean radiant temperature and air temperature between 18°C and 26°C . For the assessment of thermal comfort in this study, zone mean air temperature was taken into consideration. The comfort range was assumed to be between 18°C and 26°C . Hence, the discomfort range was both below 18°C and above 26°C , which were considered to be too cold and too hot, respectively. Comfort was assessed only during the occupied hours of each zone. Occupancy was categorised into two types—daytime use zone (living, library and lounge) and night-time use zone (two bedrooms). The hours of occupancy were assumed as:

- _ Daytime use zone: 07:00am – 10:00pm
Total annual hours: 15 hours a day x 365 days = 5,475 hours
- _ Night-time use zone: 08:00pm – 07:00am
Total annual hours: 11 hours a day x 365 days = 4,015 hours

Procedure for analysis of thermal comfort

After running an annual simulation on the reference simulation model, discomfort hours based on the zone mean air temperature were calculated. For the improvement of thermal comfort performance, design strategies were introduced such that the discomfort hours in each of the five thermal zones was reduced by at least 50% in the final model. Through a comparative analysis, this paper aimed to improve the performance of a naturally ventilated residence by incorporating design strategies to increase thermal comfort in a temperate climate.

Design controls for the intervention models

For the improvement of thermal performance between the reference and final model by 50%, the design controls to be followed were:

- _ The overall dimension, orientation and interior layout of the building could not be altered.
- _ The internal load assumptions such as occupancy, lighting and equipment and their operation schedule were to be constant.
- _ Passive solar design and climate responsive strategies aimed at modulating and controlling the building fabric could be implemented.

Procedure for review of results

Following simulation run of the reference simulation model, the calculation of the annual discomfort hours was carried out using the CSV file generated by EnergyPlus. Results were reviewed within the DesignBuilder interface as well as through the HTML report and ESO file generated by EnergyPlus. After the implementation of each design strategy, a simulation run was carried out followed by the same review process. This paper includes the detailed description of design strategies adopted in each simulation run along with the analysis of output reports. All the implemented design strategies were analysed to identify the most effective solutions to improve thermal comfort performance in a naturally ventilated residence.

Results and Discussion

Analysis of Reference Simulation Model

The reference model was simulated for an entire year. In this paper, only the mean zone air temperature was taken into consideration. Comfort and discomfort hours were calculated assuming comfort range to be between 18°C and 26°C. Occupancy was considered seven days a week all year long, with a specific time frame for daytime use zone (07:00am – 10:00pm) and night-time use zone (08:00pm – 07:00am). The target discomfort hours calculated were 50% of the total discomfort hours for each zone. Table 3 outlines the simulation results of the reference model in DesignBuilder.

Table 3

Annual comfort and discomfort hours from simulation of reference model.

Location	Day Zones			Night Zones	
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
	Library	Living	Lounge	Bedroom 1	Bedroom 2
	Ground Floor	Ground Floor	First Floor	Ground Floor	First Floor
Total comfort hours	1444	1100	1167.5	189.5	198.5
Total discomfort hours	4031	4375	4307.5	3825.5	3816.5
< 18°C	3966.5	4245.5	4166	3825.5	3816.5
> 26°C	64.5	129.5	141	0	0
Total annual hours	5475	5475	5475	4015	4015
Comfort (%)	26.37	20.09	21.32	4.72	4.94
Discomfort (%)	73.63	79.91	78.68	95.28	95.06
Target discomfort (%)	36.81	39.95	39.34	47.64	47.53
Target discomfort hours	2015.5	2187.5	2153.75	1912.75	1908.25

A large proportion of annual discomfort hours were due to temperatures below 18°C in all zones. The results indicate the need of passive solar design strategies to increase the thermal comfort levels particularly in winter. Fig. 5 illustrates the sun path diagrams and the effect of solar access and sun shading on each zone. The bedrooms located in the north-east corner only received morning sun and were mostly shaded, which may account for the high discomfort hours. The orientation of the living room and lounge towards the south ensured sunlight penetration throughout the day, while the library located on the west received evening sun. Nonetheless, the discomfort hours in all zones were extremely high, accounting for over 70% of the total annual hours.

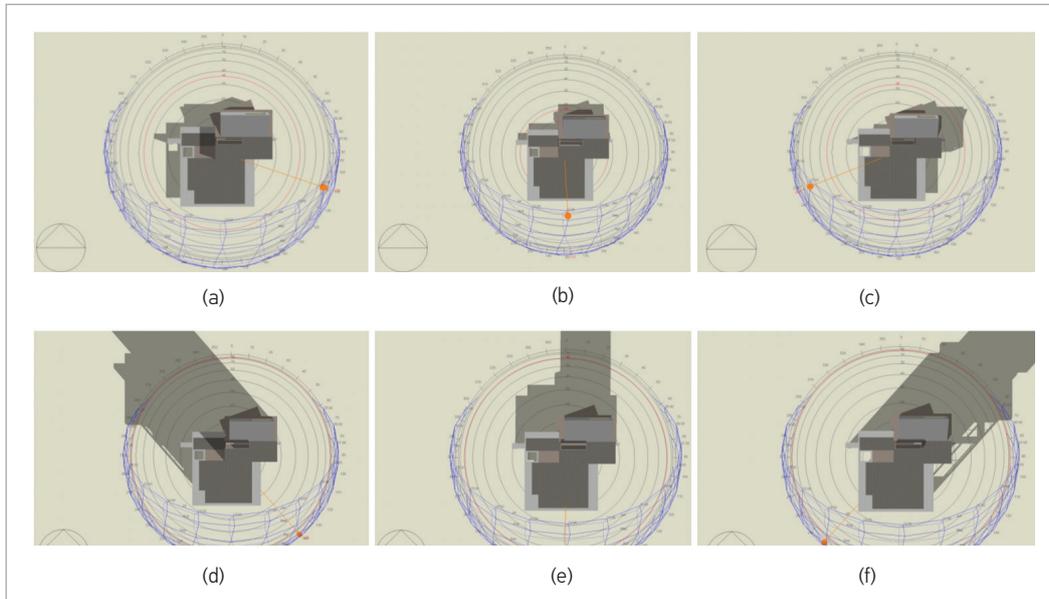


Fig. 5

Sun path diagrams (a) 9am 21 June (Summer Solstice) (b) 12pm 21 June (c) 3pm 21 June (d) 9am 21 December (Winter Solstice) (e) 12pm 21 December (f) 3pm 21 December

Fig. 6 illustrates the comfort graph generated from the simulation of the reference model. Only the temperatures of the summer months were under the comfort range of 18 to 26°C. The indoor air temperature and outside dry-bulb temperature had minor differences throughout the year, which may cause temperature fluctuation within the residence and increase discomfort. Across

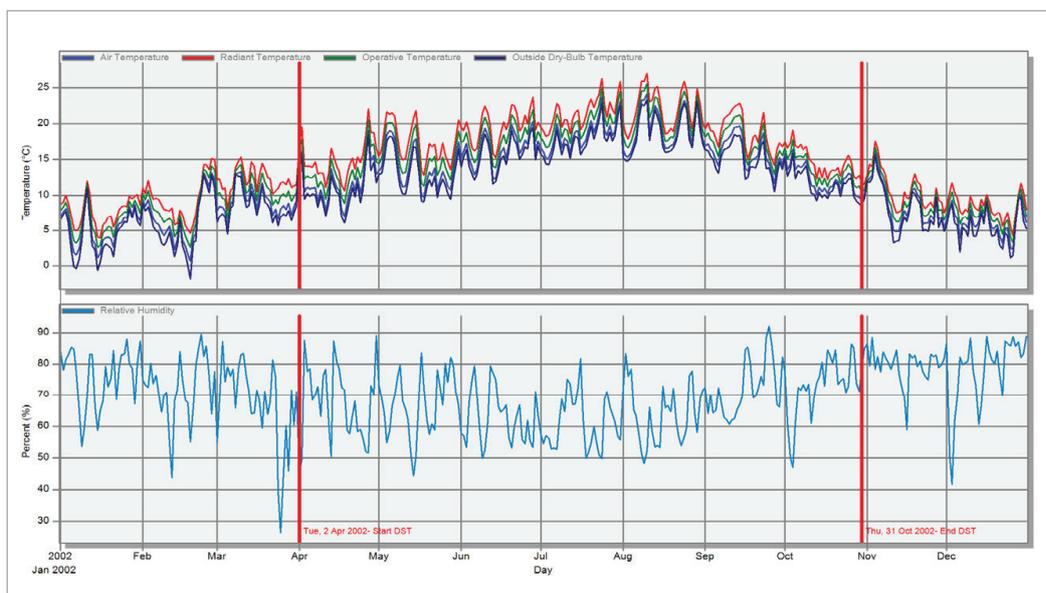


Fig. 6

Annual comfort chart of reference simulation model with temperature and relative humidity.

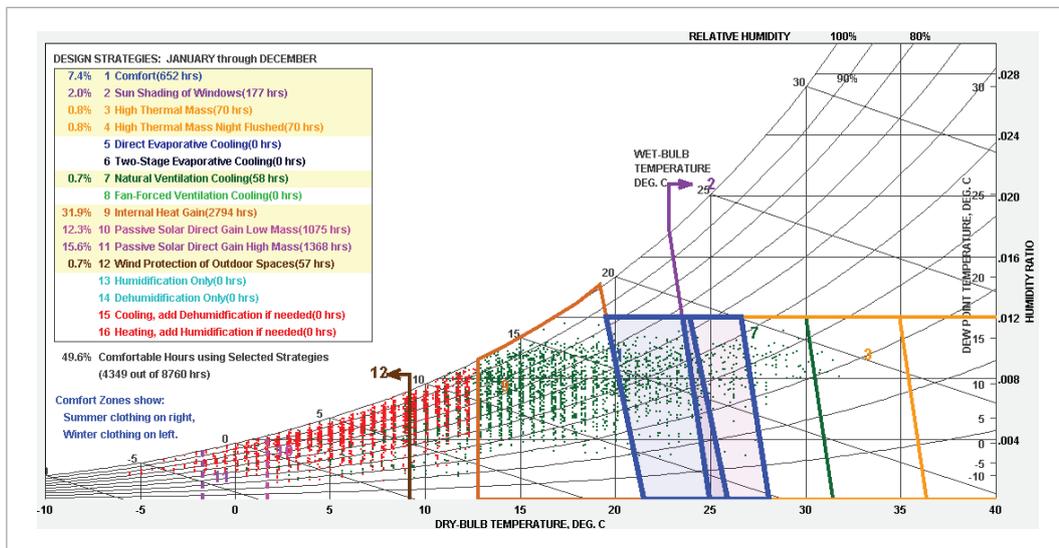
the year, the relative humidity was also in the higher range, mostly exceeding the comfort range of 30-60% as recommended by ASHRAE (2016).

Potential Design Strategies for the Intervention Models

The climate analysis for Seattle-Tacoma International Airport was conducted using Climate Consultant program, which is an easy-to-use tool to evaluate the effectiveness of active and passive design strategies. Using standardised weather data for energy simulation software, the graphic-based tool can perform thermal comfort calculations and provide thermal comfort visualisation (Schiavon et al., 2014). Among the four comfort models available, ASHRAE Standard 55-2004 using Predicted Mean Vote (PMV) was selected, on the basis of which the psychrometric chart and the design strategies are provided. Fig. 7 represents the psychrometric chart illustrating the ASHRAE Standard 55-2004 thermal comfort zones calculated with the PMV method and the thermal zones corresponding to selected design strategies for the climate of Seattle-Tacoma International Airport. The psychrometric chart indicates that using the design strategies currently adopted in the reference simulation model, an indoor comfort level of only 50% can be achieved without the use of any active systems of heating and cooling. This finding suggests that it will be a challenge to significantly improve thermal comfort in a naturally ventilated residence.

Fig. 7

Psychrometric chart for Seattle-Tacoma International Airport generated by Climate Consultant based on design strategies used in the reference simulation model



The Climate Consultant software also provided a list of residential design guidelines for the particular climate, using the best set of design strategies to maximise comfort hours. These design guidelines are also based on ASHRAE Standard 55-2004 using PMV, and were taken as reference for the proposal of design strategies to improve thermal performance:

- For passive solar heating face most of the glass area south to maximise winter sun exposure, but design overhangs to fully shade in summer.
- Provide double pane high performance glazing (Low-Emissivity) on west, north and east, but clear on south for maximum passive solar gain.
- Heat gain from lights, people and equipment greatly reduces heating needs so keep home tight and well insulated.
- Traditional passive homes in cool overcast climates use low mass tightly sealed, well insulated construction to provide rapid heat build-up in morning.
- Use high mass interior surfaces like slab floors and high mass walls to store winter passive heat and summer night coolth.

- _ Pitched roof, with a vented attic over a well-insulated ceiling works well in cold climates
- _ Sunny wind-protected outdoor spaces can extend living areas in cool weather.
- _ Extra insulation (super insulation) might prove cost effective and will increase occupant comfort by keeping indoor temperatures more uniform.
- _ Small well-insulated skylights (less than 3% of floor area in clear climates, and 5% in over-cast) reduce daytime lighting energy and cooling loads.
- _ Windows can be unshaded and face in any direction because any passive solar gain is a benefit, and there is little danger of overheating.

Adoption of Design Strategies

Design process

Following review of literature on the potential design strategies for a temperate climate as well as the design guidelines suggested by Climate Consultant, a set of design strategies were implemented in the reference simulation model. To keep track of progress, annual simulation was conducted after each strategy was introduced, followed by calculation of discomfort hours. The output data were analysed, and necessary changes were made accordingly. The design process anticipated a decrease in discomfort hours in each simulation run to ultimately achieve a reduction of 50% in each zone in the final intervention model. A total of 12 simulation runs were conducted integrating a particular strategy that showed positive results. A set of these design strategies and simulations have been combined as four interventions and are reported in this paper (Table 4). Moreover, rationale behind the use of each strategy and the results obtained are discussed, which is further supported by available literature on the topic.

	Annual discomfort hours and percentage reduction from the reference simulation model					
	Reference Simulation Model	Target Model **	Intervention 1 Model	Intervention 2 Model	Intervention 3 Model	Intervention 4/ Final Intervention Model
Zone 1: Library	4031	2015.5 (50%)	3505.5 (13.04%)	3390.5 (15.89%)	2290.5 (43.18%)	1893.5* (53.03%)
Zone 2: Living	4375	2187.5 (50%)	4057 (7.27%)	4050.5 (7.42%)	2780 (36.46%)	2453 (43.93%)
Zone 3: Lounge	4307.5	2153.75 (50%)	3991 (7.35%)	3880 (9.92%)	2910.5 (32.43%)	2326.5 (45.99%)
Zone 4: Bedroom 1	3825.5	1912.75 (50%)	3359 (12.19%)	3269 (14.55%)	1744.5* (54.40%)	1514* (60.42%)
Zone 5: Bedroom 2	3816.5	1908.25 (50%)	3248.5 (14.88%)	3123.5 (18.16%)	1952 (48.85%)	1567* (58.94%)

* Target discomfort hours met. ** Target of 50% reduction of discomfort hours from the reference simulation model.

Intervention 1: Triple glazed low-emissivity openings

Focusing on increasing insulation performance, the glazing for all openings was modified from single glazing to triple glazing as used in the case study residence and as suggested by Climate Consultant. Especially for the climate of Seattle, triple glazing with a low-emissivity (LoE) coating is recommended as an ideal design strategy to provide insulation in winter and avoid heat gain in summer (Passive Solar Industries Council, 1991). This LoE coating ensures that the heat transfer between indoor and outdoor space is reduced and the insulation properties of the opening is improved (Aguilar-Santana et al., 2019). Apart from glazing, other components of openings such as the gaps between glass panes and window frame also account for heat transfer. Gas-filled cavities

Table 4

Thermal comfort performance simulation results presented across interventions

such as argon can significantly reduce the thermal transmittance or U-value of openings. Therefore, triple glazing, clear, LoE, argon filled glazing template was selected for the intervention model, considering these factors. In terms of window frame, wooden frames have superior insulation due to low thermal transmittance (Van Den Bossche et al., 2015), while aluminium frames have high conductivity and a higher U-value (Sinha and Kutnar, 2012). Hence, the aluminium frame for all openings were replaced with painted wooden frames for durability and insulation. The specific modifications, opening type and glazing properties are outlined in Table 5. These strategies were focused on improving the thermal performance of all components of openings.

Table 5

Opening type and glazing properties in the reference simulation model and intervention model

	Reference Simulation Model	Intervention Model
Glazing template	Single glazing, clear, no shading	Triple glazing, clear, LoE, argon filled
Glazing Type	Single clear 6mm	Trp LoE (e2=e5=.1) Clr 3mm/13mm Arg From outside to inside: LoE clear 3mm, Argon 13mm, Clear 3mm, Argon 13mm, LoE clear 3mm
U-value (W/m ² K)	5.8	0.786
Solar heat gain coefficient (SHGC)	0.86	0.470
Visible light transmittance (VLT)	0.88	0.661
Construction of frames	Aluminum window frame	Painted wooden window frame

Following the simulation of the intervention model, a significant improvement in thermal comfort was observed (Table 4). The reduction in annual discomfort hours ranged from 7.27% to 14.88% across the five zones. Moreover, this intervention mostly reduced the discomfort hours arising due to temperatures below 18°C in all zones, which supports the importance of high insulation opening systems for increasing comfort in winter.

Intervention 2: Energy code standard construction

As per the location set in the reference simulation model and the EnergyPlus weather data for the location uploaded in DesignBuilder, the ASHRAE climate zone was set as “4C” for Seattle-Tacoma International Airport. On the basis of these information, DesignBuilder provides construction templates using four standard insulation levels – uninsulated, typical, energy code, and best practice (DesignBuilder Software Ltd, 2021). The energy code template is based on the maximum U-values allowed in the energy code or building regulations. The uninsulated construction in the reference simulation model was replaced with energy code standard in this intervention model. The “energy code standard medium weight construction” template was individually applied to the construction systems of external wall, ground/internal floor, flat roof and pitched roof (Table 6). However, the construction materials used in the reference simulation model were retained, as far as possible, with the intervention focusing on modification of the construction to thermally medium weight elements with a standard specification of insulation materials, which comply with the energy codes/building regulations.

Changing the uninsulated construction to energy code standard was expected to cause a drastic reduction in discomfort hours. However, the simulation results (Table 4) demonstrate a minor improvement in thermal comfort between interventions 1 and 2, with around 0.15% to 3.28% reduction in discomfort hours in each zone. The improvement observed was largely attributed to the reduction of temperatures falling below 18°C. Hence, it is evident that an insulated construction minimises heat loss during winter. Application of thermal insulation is one of the fundamental passive design strategies, which can directly determine occupant comfort (Omran and Marso-

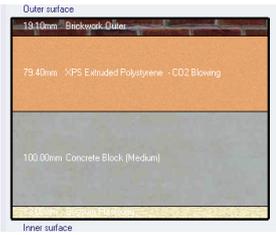
Construction Materials Specification	Schematic Diagram
<p>External Wall:</p> <ul style="list-style-type: none"> _ 19.10mm brickwork _ 79.40mm XPS extruded polystyrene _ 100mm medium concrete block _ 13mm gypsum plastering _ R-value ($\text{m}^2\text{K}/\text{W}$): 2.853 _ U-value ($\text{W}/\text{m}^2\text{K}$): 0.351 	
<p>Ground/Internal Floor:</p> <ul style="list-style-type: none"> _ 30mm timber flooring _ 70mm screed _ 100mm cast concrete _ 19.10mm urea formaldehyde foam _ R-value ($\text{m}^2\text{K}/\text{W}$): 3.184 _ U-value ($\text{W}/\text{m}^2\text{K}$): 0.314 	
<p>Flat Roof:</p> <ul style="list-style-type: none"> _ 19.10mm asphalt _ 13mm fiberboard _ 48mm XPS extruded polystyrene _ 100mm lightweight cast concrete _ R-value ($\text{m}^2\text{K}/\text{W}$): 2.059 _ U-value ($\text{W}/\text{m}^2\text{K}$): 0.486 	
<p>Pitched Roof:</p> <ul style="list-style-type: none"> _ 25mm roofing clay tile _ 181.90 mm MW stone wool _ 5mm roofing felt _ R-value ($\text{m}^2\text{K}/\text{W}$): 4.348 _ U-value ($\text{W}/\text{m}^2\text{K}$): 0.230 	

Table 6

Specifications of construction materials in the intervention 2 model

no, 2016). Along with restricting heat transfer between indoors and outdoors, thermal insulation ensures that the indoor air temperature remains at a relatively constant level. Only the minor improvement in thermal comfort may be partly explained by the use of thermal mass in the reference simulation model itself. The hollow concrete block walls and cast concrete floors and roof function as thermal mass, with the ability to absorb, store and release heat, and acting as heat sink during day and heat source during night (Shafiq et al., 2018). In this intervention, insulation layer was applied on the exterior side of the thermal mass, as this strategy generally results in heat gain during harsh winter, reduced risk of overheating in summer, and indoor environments with minor temperature fluctuations (Roberz et al., 2017).

Intervention 3: Windows and operation schedule

With the assumption that the remainder of the discomfort hours could be attributed to the openings, this intervention integrated a number of strategies focused on modifying the windows and operation schedule. Firstly, only the windows of ground floor—bedroom 1 were taken into consideration. Of the three windows in the east façade, the size of one floor-to-ceiling window was reduced, while another narrow-elongated window was removed (Fig. 8). In bedroom 1, the similar floor-to-ceiling window in the west façade was also reduced. These minor changes would not sig-

nificantly affect the daylighting levels and would further ensure privacy in the bedroom. Secondly, the operation schedule of all openings was taken into consideration. As shown on Fig. 8, most of the openings in the case study residence had a top hung window above the operable windows. The operation schedules of these top-hung windows were changed from “on 24/7” to “off 24/7”, such that these would only serve the purpose of daylighting and not ventilation.

Fig. 8

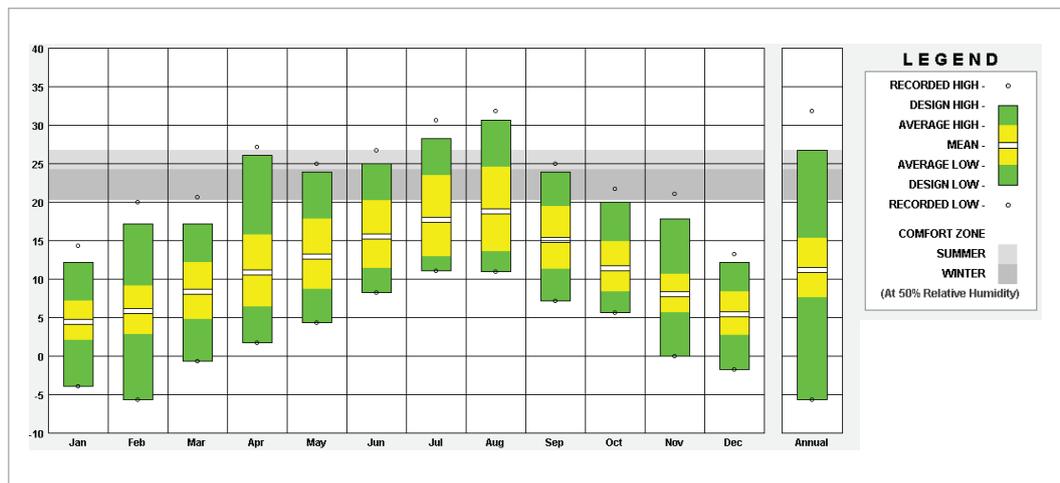
East façade (a) Reference simulation model. (b) Intervention 3 model



Thirdly, modification of operation schedule for all other windows were conducted as per the analysis of the annual temperature range (Fig. 9). As an attempt to further reduce the discomfort hours in both temperatures below 18°C (winter) and above 26°C (summer), the operation schedules for all windows (except the aforementioned top hung windows) were taken into consideration. These were modified from “on 24/7” to “on” in June, July and August (summer); “on during day” (9am – 6pm) in April, May and September; and off in other winter months. The day operation schedule was set specifically for spring and autumn seasons to minimise heat loss at night. The residence was fully ventilated in summer to cool the spaces and sealed shut in winter to minimise heat loss.

Fig. 9

Annual temperature range of Seattle-Tacoma International Airport (Source: Climate Consultant)



Following the adoption of these design strategies, the simulation results (Table 4) demonstrated an extensive improvement in thermal comfort. The reduction in annual discomfort hours from intervention 2 to 3 ranged from 22.51% to 39.85% across the five zones. More importantly, the target discomfort hours were met in bedroom 1, with 54.40% reduction in discomfort hours from the reference model, as a result of the modification of operation schedule and the specific reduction of openings in bedroom 1. Incoming air is detrimental to thermal comfort particularly in the winter, while ventilation can be used to cool the building in other seasons (Moret Rodrigues et al., 2019). It is evident from the results that rather than ventilating, insulating the residence in winter

largely improved the thermal comfort performance. On the other hand, natural ventilation across summer, and particularly throughout the day in spring and autumn seasons, showed a major reduction of discomfort hours. Gao and Lee (2011) also found full-day ventilation to be a better option in a hot and humid climate as compared to night ventilation. These findings indicate that in a naturally ventilated residence, control of ventilation levels through optimisation of windows operation schedule is paramount to achieve thermal comfort.

Intervention 4: Windows and shading, operation schedule, and construction

This intervention focused on introducing a number of design strategies specifically for summer months, to reduce the discomfort hours due to temperatures above 26°C. Firstly, window shading with blinds was incorporated in all windows. Secondly, the design strategies were focused on increasing thermal comfort in day spaces, namely living room, lounge and library. The south facing windows account for solar heat gain in winter, however, to protect from excessive heating in summer, overhangs were integrated. On the east façade, the size of the glazed doors of living room and window of lounge were also reduced for the same purpose (Fig. 10 a and b). Thirdly, this intervention aimed to minimise the harsh rays of setting sun in the west façade. The west-facing window of the living room was removed and the size of that of bedroom 2 was reduced (Fig. 10 c and d). An overhang was also placed in west-facing window of the library. The size of the floor-to-ceiling window in bedroom 1 was already reduced in intervention 3.

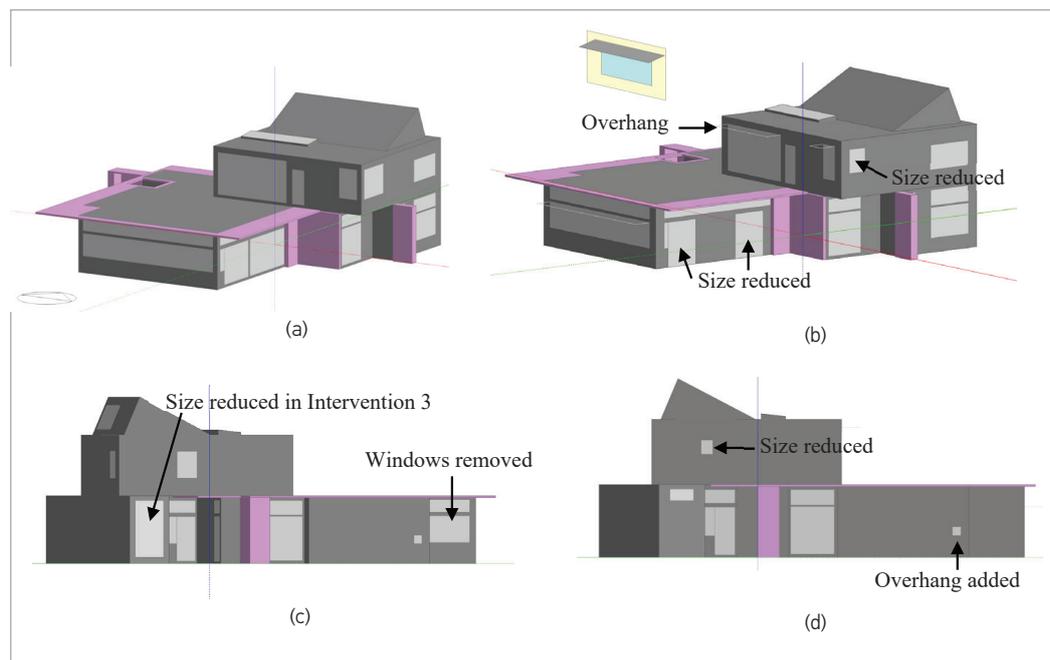


Fig. 10

(a) Reference model south/east façade. (b) Intervention model south/east façade. (c) Reference model west façade. (d) Intervention model west façade

In order to further optimise and control natural ventilation, a custom window operation schedule was developed for each zone:

- Bedroom 1 and 2: “on during day” (10am – 6pm) from April to September, and “off” during the other cooler months.
- Lounge: “on during day” (10am – 6pm) in June, July and September, “on from 2pm – 6pm” in May and October, “on” during August, and “off” during other cooler months.
- Living: “on during day” (10am – 6pm) in May, June and September, “on from 2pm – 6pm” in April and October, “on” during July and August, and “off” during other months.

- Library: “on during day” (10am – 6pm) in May and September, “on from 2pm – 6pm” in April, “on” during June, July and August, and “off” during other cooler months.

The operation schedule was individualised on the basis of the mean air temperature for each zone, such that natural ventilation could be used as a passive cooling strategy to reduce the discomfort hours above 26°C, whilst controlling it to avoid heat loss during cooler months.

Lastly, this intervention focused on further insulating the residence as an attempt to minimise heat transfer and improve thermal comfort. The construction systems as mentioned in intervention 2 (Table 6) were modified, primarily for addition of insulation and increment of thermal resistance (R-values) of construction elements. The modifications of the external wall, ground floor and internal floor undertaken in this intervention are outlined in Table 7.

Table 7

Specifications of construction materials in the intervention 4 model

Construction Materials Specification	Schematic Diagram
<p>External Wall:</p> <ul style="list-style-type: none"> 101.6mm wood (4-inch wood, 2x4 at R-1.25/inch) 150mm glass-fibre batt insulation (R-11+R-11) 100mm brickwork outer 150mm XPS extruded polystyrene 100mm medium concrete block 13mm gypsum plastering R-value (m^2K/W): 8.519 U-value (W/m^2K): 0.117 	
<p>Ground Floor:</p> <ul style="list-style-type: none"> 30mm timber flooring 100mm glass fibre/wool fibre quilt 70mm screed 100mm cast concrete 100mm urea formaldehyde foam R-value (m^2K/W): 5.648 U-value (W/m^2K): 0.176 	
<p>Internal Floor:</p> <ul style="list-style-type: none"> 30mm timber flooring 70mm glass fibre/wool fibre quilt 100mm cast concrete 70mm glass fibre/wool fibre quilt 15mm fibreboard R-value (m^2K/W): 4.268 U-value (m^2K/W): 0.235 	

Following the simulation of the intervention model, a significant improvement in thermal comfort was observed (Table 4), with 6.03% to 13.56% reduction in annual discomfort hours across the five zones from intervention 3 to 4. Moreover, the target discomfort hours were met in three of the five zones. Orientation of openings is a vital component in passive solar design. South-facing windows receive ample sunlight throughout the day, allowing to absorb and distribute sun's energy to keep the building warm across winter (Green Passive Solar Magazine, 2021). However, effective shading of these windows through a shading system or an overhang is integral to prevent overheating and keep the building cool in summer (Imperadori et al., 2004).

While the east-facing windows catch the morning sun, these do not provide significant energy, yet can cause major overheating in summer (Passive Solar Industries Council, 1991). Similarly, west-facing windows allow the setting sun to penetrate despite the installation of shading systems, hence causing significant overheating in summer. Informed from literature review, the design strategies integrated in this intervention such as shading of south-facing windows, reduced size of east-facing openings, and reduced size and removal of some windows in the west façade showed promising results. The results also demonstrated the importance of individualised control of windows operation schedule. Natural ventilation is a vital passive cooling strategy for warmer months, which should be optimised to maximise thermal comfort performance. In this study, the window operation schedule for each zone was set manually based on the mean air temperature. Alternatively, automated window control could be particularly useful in a naturally ventilated residence (da Graça et al., 2004). The temperature sensor device is installed on the windows, which opens or closes the windows on the basis of the set-point temperature. Lastly, the addition of insulation in the walls and floors can also significantly improve the thermal performance, which is evident from the positive results. The Passive House Standard also focuses on increasing energy efficiency through a highly insulated and tightly sealed building envelope (Sage-Lauck and Sailor, 2014). However, this may cause overheating in summer, which should be balanced by naturally ventilating the space for passive cooling.

Analysis of Final Intervention Model

The intervention 4 model was considered as the final intervention model. As an attempt to further reduce the discomfort hours, several strategies were introduced in the intervention 4 model. Nonetheless, no significant improvement was observed through the modification of construction materials, operation schedule and building fabric, and thus were disregarded. It is important to consider that the intervention 4 model or the final intervention model integrated the best set of possible design strategies to improve thermal comfort. The different views of the final intervention model are presented in Fig. 11.

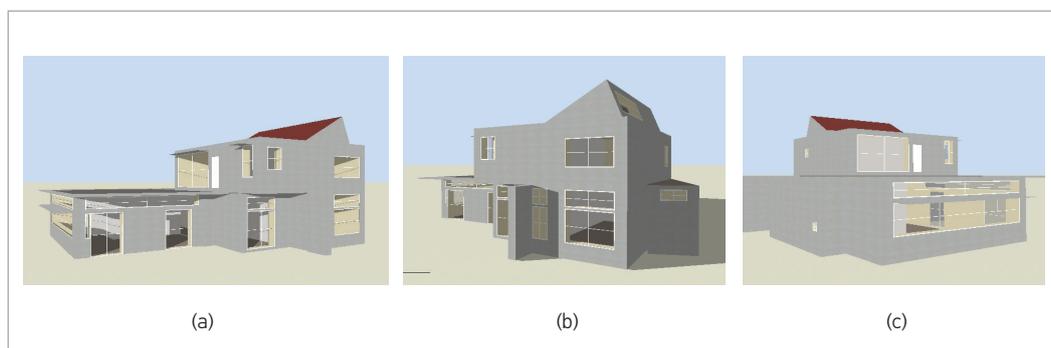


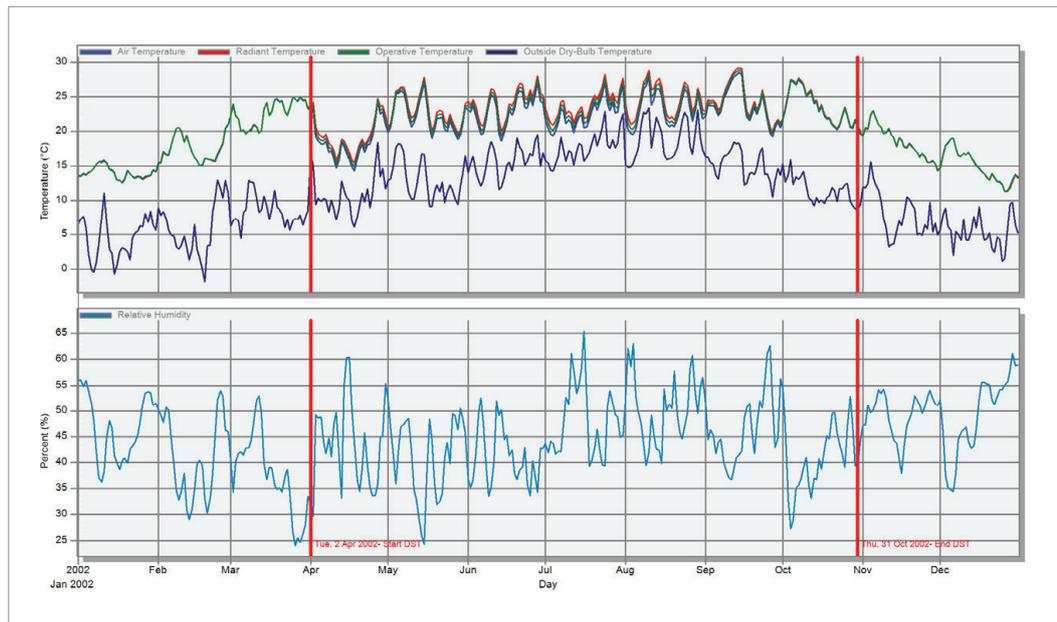
Fig. 11

Final intervention model
(a) South/east façade.
(b) North/east façade. (c)
East/west façade

Fig. 12 represents the comfort graph generated through the annual simulation of the final intervention model. It is evident that the temperatures inside the residence had minor fluctuations across the year, were substantially higher than the outside dry-bulb temperature, and with majority of the air temperature falling in the comfort range. The integration of design strategies has improved the thermal performance of the residence to a large extent, which is well-explained by the minor differences in air, radiant and operative temperatures. However, there was still a room for improvement, particularly in the summer seasons. On the other hand, the relative humidity was also improved with majority falling with the comfort range of 30-60% as recommended by ASHRAE (2016).

Fig. 12

Annual comfort chart of final intervention model with temperature and relative humidity



Discussion of Results

In this study, a reference simulation model was developed in DesignBuilder by referring to the orientation and massing of a naturally ventilated case study residence, and the annual discomfort hours were calculated for five zones. Four major interventions, each integrating a set of design strategies were introduced, with the aim of reducing the discomfort hours by 50%. The target discomfort hours were met in three zones, namely library, bedroom 1 and bedroom 2, with 53.03%, 60.42% and 58.94% reduction in discomfort hours, respectively. The two remaining zones, living and lounge, also had a notable improvement, with 43.93% and 45.99% reduction in discomfort hours (Table 4). Of the four interventions, the most effective was intervention 3 (windows and operation schedule), followed by intervention 1 (triple glazed low-emissivity openings), intervention 4 (windows and shading, operation schedule, and construction), and intervention 2 (energy code standard construction).

Fig. 13 provides a comparison and distribution of the annual discomfort hours between the reference simulation model and final intervention model. In the final model, the discomfort hours arising due to temperatures below 18°C reduced by 61.75% to 67.13% across the five zones. This finding suggests that the design strategies such as increasing the insulation performance of openings and construction systems, maximising solar heat gain in winter, and optimising the windows operation schedule among others, were successful in improving thermal comfort particularly in colder months. On the other hand, there was an increase in the number of discomfort hours attributed to temperatures above 26°C in the final model. This may be a result of the design strategies adopted to minimise the uncomfortably cool hours, including the addition of a highly insulated building envelope. Nonetheless, the final model did integrate several strategies to mitigate the uncomfortably hot hours such as natural ventilation for passive cooling, reduction or removal of windows, and addition of shading. In the final model, the annual comfort hours achieved in library, living, lounge, bedroom 1 and bedroom 2 were 65.42%, 55.20%, 57.51%, 62.29% and 60.97%, respectively. This was a major improvement from the 26.37%, 20.09%, 21.32%, 4.72% and 4.94% annual comfort hours obtained in the reference model. Nonetheless, it is evident from the results that it is a challenge to achieve optimum thermal comfort in a naturally ventilated building throughout the year with the use of passive design strategies alone.

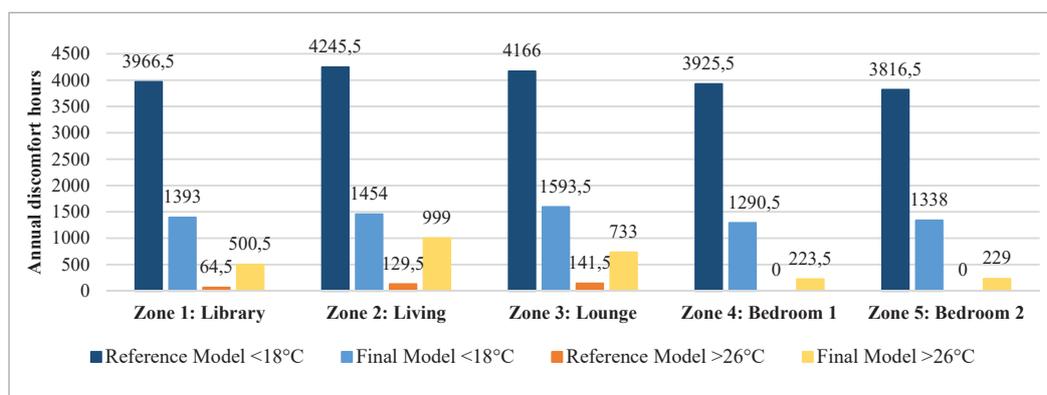


Fig. 13

Comparison of annual discomfort hours between the reference model and final model

Additional design strategies are recommended in order to successfully reduce the discomfort hours in each zone by 50% or more, as compared to the reference simulation model. Air infiltration was not considered in both the reference and final models. As air leakage accounts for both heat loss and gain, it is a major factor of thermal comfort. Apart from a highly insulated envelope, the Passive House Standard also emphasises on achieving a tightly sealed building envelope, with air infiltration less than or equal to 0.6 air changes per hour at a 50 Pa indoor–outdoor pressure difference (Sage-Lauck and Sailor, 2014). Secondly, rather than setting fixed timings for windows operation, automated windows that operate according to the set comfort temperature range may further optimise the natural ventilation to improve thermal comfort. Finally, the shading of the openings could also be customised to follow a specific pattern according to the sun path such that heat gain can be minimised particularly in summer, whilst aiding in solar heat gain in the winter.

A two-storey naturally ventilated residence located in Washington, United States with a temperate climate was selected as the case study residence. The residence integrated a number of passive design strategies such as east-west orientation for sunlight and wind penetration, thermal mass walls of concrete masonry unit for heat source and sink, east and south facing openings along the sun path, and mechanical skylight vents for stack effect and natural ventilation. A reference simulation model was developed by replicating only the orientation and massing of the case study residence, while certain assumptions were made for other building characteristics. Thermal comfort performance analysis was conducted in the DesignBuilder software. With the help of passive design strategies, a 50% reduction in the annual discomfort hours in the five selected zones was anticipated from the reference simulation model to the final intervention model. Following the integration of four major interventions, the target discomfort hours were met in three zones, namely library, bedroom 1 and bedroom 2, with 53.03%, 60.42% and 58.94% reduction in discomfort hours, respectively. The two remaining zones, living and lounge, also had a notable improvement with a reduction of 43.93% and 45.99%, respectively.

The most effective intervention for improving thermal comfort performance was the customisation of the window operation schedule for each zone based on seasonal air temperature differences, such that natural ventilation could be used as a passive cooling strategy in warmer months, whilst controlling it to insulate the building and avoid heat loss in cooler months. The importance of improving the thermal performance of all window components was also observed, as evidenced by the significant improvement in thermal comfort due to triple glazed, low-emissivity and argon filled openings with wooden frames. Openings-based interventions to minimise solar heat gain and overheating in summer such as integrating overhangs in south-facing windows, minor reduction of openings in the east and west façade, and addition of blinds for shading in windows also showed promising results. The improvement in thermal comfort attributed to the use of an

Conclusions

energy code standard construction for the building components highlights the importance of thermal resistance and insulation to minimise indoor air temperature fluctuations. Further addition of insulation in the building envelope was found to be an effective passive design strategy as shown by the further improvement in thermal comfort performance. It is evident from the results that achieving optimum thermal comfort in a naturally ventilated residence with the use of passive design strategies alone can be challenging. Nonetheless, with the appropriate use of passive heating and cooling strategies, occupant thermal comfort can be significantly improved throughout the year, whilst minimising both the energy consumption and environmental impact of buildings.

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About the Author

KRITIKA RANA

Postgraduate Student

School of Architecture, Design and Planning, University of Sydney

Main research area

Sustainable architecture, high-performance buildings, housing and health research

Address

Auburn, NSW 2144, Australia

Tel.: +61280407492

E-mail: r.kritika@live.com

