Improving Building Thermal Performance Through an Integration of Passivhaus Envelope and Shading in a Tropical Climate

Abstract

Due to the success of the energy-efficient Passivhaus building envelope and its principles in regulating indoor thermal comfort in European climates, the potential implementation of it in other climates has been subjected to much attention in recent years. In this work, we adopted the hypothesis that slightly higher U-values of walls and floors than Passivhaus suggestion could be sufficient to achieve Passivhaus targets in the tropical context if the synergistic effects between shading and building envelope design were considered in a naturally ventilated condition.

Firstly, thermal comfort thresholds were reviewed to establish the boundaries in the tropical context, choosing Myanmar as a case study. Secondly, Passivhaus steady-state calculation for shading design was compared with other dynamic simulation programs to inform the next step. The impacts of other parameters, which were excluded in Passihvuas's PHPP calculation, were then investigated. Finally, thirty shading scenarios for ten different building envelopes were analysed in free-running modes using typical and future weather scenarios. The results showed that the hypothesis was true and 3.6% of annual overheating hours were reduced by coupling Passivhaus building envelope, thermal mass and shading devices, and also overall extremes of temperature were reduced by more than 2.4K on the hottest day.

Keywords: Building thermal performance; Passivhaus; Climate change; Overheating; Shading.

1 Introduction

Whilst the Passivhaus concept with shading strategy is theoretically successful and practically achievable for free-cooling resources, understanding the characteristics of Passivhaus implementations in different climate zones is imperative (Schnieders et al., 2012, Schnieders et al., 2015, Schnieders et al., 2019, James and Bill, 2016). The Passive-On project for European warm climates highlighted possible solutions to address through the use of comfort models, related climate contexts, passive measures and active strategies (Schiano-Phan et al., 2007). An actual building case study, which was designed based on low energy principles from the Passivhaus standard, also shows that mechanical ventilation with heat recovery may not be necessary or desirable for the UK context (Schiano-Phan et al., 2008). For a tropical context, coupling several passive cooling approaches in the Passivhaus building envelope, including thermal mass and shading devices, could have a significant advantage in a naturally ventilated condition. There is a gap in the current literature of Passivhaus building envelope design in a free-running mode (no active cooling or heating in an adaptive comfort model) for a tropical context, and therefore, the focus of this work.

Passivhaus is a building design and delivery concept created by the Passivhaus Institute (PHI) that suggests a set of design criteria developed to limit operational energy used whilst achieving maximum thermal comfort (Passivhaus Trust, 2020, Feist et al., 2019, iPHA, 2016), and can be certified through an exacting quality assurance process (Gonzalo and Valentin, 2014). The concept is originally based on the idea for cold climates that if heat losses are reduced to an absolute minimum, the building hardly needs any heating and therefore can become comfortable mostly through the maximisation of passive heat sources like the sun, occupants and appliances (Feist et al., 2005, Passive House Institute, 2014). The Passivhaus standard holistically incorporates five basic principles (Passive House Institute, 2015): superinsulation, thermal bridge free construction, airtight building envelope, high-performance specifications for windows and doors, and mechanical ventilation with a heat recovery system (MVHR). The first four principles of Passivhaus are known as the fabric-first approach, which minimises all heat flows into and within the building envelope, to provide comfortable indoor conditions with extremely low heating and cooling loads (Schnieders et al., 2015). For instance, a 273 mm thickness brick cavity wall has the thermal transmittance value (U-value) of 1.44 to 1.77 W/(m^{2}K) (CIBSE, 2015), whereas the typical U-values for the opaque envelope in a Central European Passivhaus range from 0.10 to 0.15 W/(m^{2}K) (Feist et al., 2019) to reduce heat transfer dramatically through the use of superinsulation. Using the Passive House Planning Package (PHPP), the Passivhaus standard uses the heat balance method for steady-state calculations considering a super-insulated building is applied an ‘active’ approach of pre-heat or pre-cool incoming fresh air to meet the heating or cooling requirements (Hodgson, 2008). Furthermore, the successful implementation of the Passivhaus concept is heavily dependent on the thermal bridge free and airtight construction of the building envelope (Gonzalo and Valentin, 2014). On the contrary, a vernacular lightweight wall in the tropic has small or no thermal insulation; thermal bridges are therefore hardly an issue because of the small temperature differences between indoor and outdoor, while an adaptive comfort model is considered. When a Passivhaus building is highly insulated to offset an intense outdoor air temperature, shading plays a crucial role in the tropics to avoid direct solar gain on insulated surfaces that could lead to significant temperature differences between the outdoor and indoor surfaces; all together also can cause thermal bridging throughout the envelope. Despite differences in climate contexts, a hygro-thermal dynamic simulation study shows that Passivhaus principles remain the same across the world (Schnieders et al., 2015), and the Passivhaus standard can be adapted to different climates (James and Bill, 2016), including the tropics, where MVHR is used without the heat recovery (summer bypass).

Shading offers a microclimate modifier by reducing outdoor thermal stress and direct solar heat gain. Shading design often concerns aesthetics (Fiorito et al., 2016), building energy conservation (Aflaki et al., 2015), climate change adaptation (Hooff et al., 2014) for building thermal comfort; it is an important design feature for heat gain protection both in normal and extreme environments (CIBSE, 2017). The performance of shading is varied according to building parameters (Eltaweel and Su, 2017), climate elements (Valladares-Rendón et al., 2017), and occupant behaviours and preferences (Brien et al., 2013). Summer overheating risks are found in the highly insulated and airtight Passivhaus buildings despite its use of an active ventilation system (Mitchell and Natarajan, 2019). Optimisation of several design inputs for Passivhaus buildings, including external shading devices, thermal mass effect, and glazing ratios are therefore becoming increasingly relevant to prevent summer overheating even for the temperate climates of the United Kingdom (Rodrigues and Gillott, 2013, McLeod et al., 2013, Rodrigues et al., 2016, Abdulla and Rodrigues, 2016, Osterreicher and Sattler, 2018). Moreover, a building with Passivhaus envelopes will be in a passive and free-running mode if its concept of mechanical ventilation is inactive. In this stage, a combination of shading design, ventilation, and building envelope plays a role in improving building thermal performance for a tropical Passivhaus building.

Evidence also shows that Passivhaus building envelope with shading provides the required thermal comfort in a warm temperate climate of Italy (Costanzo et al., 2018), a dry-summer subtropical climate of Portugal (Ferreira and Pinheiro, 2011), a humid subtropical climate of Romania (Udrea and Badescu, 2020), a continental climate of Slovenia (Mlakar and Strancar, 2011), a subtropical desert climate of Dubai (Brumana et al., 2017) and Saudi Arabia (Aldossary et al., 2017). Those studies showed that fixed roof extensions, overhangs, and vertical movable shadings be more effective in those Passivhaus buildings. That revealed the applicability of the Passivhaus building envelope with shading for different climate contexts.

Besides 60,000 certified Passivhaus buildings worldwide (as of 2016) (Passipedia, 2018), only seven Passivhaus projects, including refurbishment, are found in the tropical countries (as of 2020) (Passive House Database, 2020). Hence, there is a scope of work to be investigated the synergistic effects between shading and Passivhaus building envelope design for a tropical climate context.

As material properties such as U-values, solar absorptivity and thermal mass significantly affect the heat loss and heat gain of a building, selecting the optimal material properties and ventilation strategies for insulation are crucial to improving the building thermal performance. It is worth noting that the Passivhaus values may be slightly higher or lower depending on the climate (Feist et al., 2019), "*depending on the boundary conditions in the individual circumstances"*, highlighted by Dr Wolfgang Feist (the founder of Passivhaus) (Michler, 2015). Unlike Passivhaus buildings for the cold climate, tropical vernacular buildings have high insulation only on the roof but the whole building envelope is highly infiltrated and there is no insulation on walls and floors (Lim, 1987, Rahman, 2007, Zune et al., 2020c, Zune et al., 2020b). However, evidence (Table 1) showed that Passivhaus buildings in tropical climates can be built with slightly higher U-values than the Passivhaus criteria for cold climates and have additional design features to meet the local contexts differently (Passive House Database, 2020, Bere, 2013, Oettl, 2012, Yeh, 2020). In Table 1, the U-values of walls represent a significant difference between the three buildings that could affect their energy performance; however, all buildings are certified and met the Passivhaus criteria of comfort and energy performance.

Table 1. Design information of new-built Passivhaus buildings in the tropical climates

	Austrian Embassy	Model House	Detached House
Location	Jakarta, Indonesia	São Gonçalo do Amarante, Brazil	Bangkok, Thailand
Climate	Tropical monsoon	Tropical wet and dry	Tropical savanna
Koppen classification	Am	Aw	Aw
Passivhaus ID	4340	5892	6340
U-values of walls, $W/(m^2K)$	0.320	0.210	0.16
Roof, $W/(m^2K)$	0.290	0.135	0.20
Floor, $W/(m^2K)$	1.100	0.138	0.20
Ventilation	Ventilation unit with 84% heat and 73% humidity recovery	Controlled ventilation, cool exchanger, 78% heat recovery.	-
Other design features	Solar water heater. Concrete core temperature control on the floor.	An irrigation system that can save up to 70% water.	Light colour finishes and shade on the walls.
Cooling load	85.2% annual total energy saving from conventional building	10 W/m^2	9 W/m^2
Cooling and dehumidification demand		69 kWh/m^2a	88 kWh/m^2a
Reference	(Oettl, 2012, Bere, 2013)	(Passive House Database, 2020)	(Yeh, 2020)

The risk of overheating in buildings and its consequent impacts on the health of occupants is a growing concern as the planet continues to warm (Lomas and Porritt, 2016). During the past 20 years, there has been a 53.7% increase in heat-related mortality in people older than 65 years, reaching a total of 296,000 deaths in 2018; 475 million vulnerable populations were exposed to heatwave events globally in 2019 (Watts et al., 2021). During 1998 to 2017, there were two spikes related to disaster deaths: the spike year of 2003 includes 72,000 killed in heatwaves in Europe that year, and the 2008 peak was caused by the 138,000 deaths from Cyclone Nargis in Myanmar (Robine et al., 2008, Wallemacq and House, 2018). Regarding heat-related climate change in Southeast Asia, trends in extreme temperature indices have been reported in Thailand with a nearly 50% increase between two global warming levels set by Paris Agreement (Limsakul, 2020); the number of heatwave days also increased continuously from north to south in Vietnam (Tran et al., 2020); a recent measured and simulated data sets highlighted that both vernacular and modern housing in Myanmar would face two challenges: high vulnerability to extreme heatwave events, and inadequate response to increased mean air temperatures (Zune et al., 2020d, Zune et al., 2020a). Whilst most tropical housing shares similar passive design practices, their vernacular passive cooling techniques would not be sufficient to achieve thermal comfort in the changing climate conditions. Among Asian countries, Myanmar was ranked second out of 183 countries in the long-term climate risk index for the period 1990-2018 (Harmeling et al., 2011, Eckstein et al., 2019); it continues to be at high risks. This makes Myanmar an ideal choice for a tropical climate context, as the location of our study and housing are a particularly relevant focus.

In this study, we explored the integration of Passivhaus concepts in Myanmar housing, particularly from the Passivhaus U-values and shading to protect the heat gain from the tropical climatic parameters. We started with the hypothesis that a slightly higher U-value for walls and floors can be more effective for the tropical climate than the very low U-value suggested by the Passivhaus standard for the cold climate. Following the hypothesis, we developed a methodology that underlined the synergistic effects between shading and Passivhaus thermal building envelope, particularly the effectiveness of thermal mass and insulation, to achieve free cooling resources even in the extreme temperature conditions of the tropical climates. We attempted to understand whether this hypothesis was true for the Myanmar climate and which other parameters influenced the comfort levels.

2 Methodology

The building energy and thermal performances of a Passivhaus building are estimated using a steady-state of heat balance thermal and energy model, which is generated from the laws of physics using PHPP. The Passivhaus uses MVHR for the heating seasons, but often relies on natural ventilation for cooling requirements. In tropical climates, if pre-cool air is not supplied by mechanical ventilation, natural ventilation with shading is the most appropriate passive cooling solution for a Passivhaus building when adopting a free-running model. It is unacceptable if a threshold of a heat balance comfort model for a cold climate is considered in an adaptive comfort model for the other climate. Therefore, we started by firstly quantifying thermal comfort for free-running Passivhaus buildings in tropical climates, which allowed us to identify different thermal comfort benchmarks for the comparison of the results generated from the simulation studies.

In the second step, we undertook a review of the steady-state PHPP calculation for shading design and compare it to other dynamic simulation programs, for example, Integrated Environmental Solutions Virtual Environment (IESVE). In this exercise, the building design parameters given for the PHPP Example file (version 8.5) (Feist et al., 2019) by the PHI were used. The example 'End-of-terrace' building is the world's first Passivhaus building in Darmstadt-Kranichstein (a city in southwest Germany). Through a review of the impacts of shading design on heating and cooling loads of a Passivhaus building employing the PHPP steady-state calculations for different climate contexts, the applicability of the Passivhaus concept was determined. This review informed the next step when we investigated the impacts of other parameters that were not included in the PHPP calculation.

Mandalay, the last royal capital and the second-largest city in Myanmar, was selected for this study. Mandalay, located at 22˚N, 96˚E, features a noticeably warm summer and an equal length of wet and dry seasons. According to the Koppen-Geiger climate classification, Mandalay exhibits an equatorial winter dry climate (Kottek et al., 2006). High solar radiation can be found during the solar time, from 09:00 to 16:00. As the solar altitude angles vary from 30˚ to 85˚ at the summer solstice solar time, a wide overhang can protect the direct intense sun and high temperature. On the contrary, Darmstadt is located at 49˚N and has a mild, warm temperate climate. Therefore, the monthly average outdoor temperature of Darmstadt is lower than 25°C, whereas the tropical climate of Mandalay has 67.8% of annual hours above the outdoor dry-bulb temperature of 25°C. Hence, the passive design used in tropical countries and cold climate countries could be significantly different according to their climatic parameters. Using psychrometric charts, Figure 1 compares the potential passive design strategies of Mandalay, Bangkok and Frankfurt (close to Darmstadt); the results showed that there were benefits of sun shading on windows and thermal mass for Mandalay. Unlike tropical cities near the Equator, for instance, compared to Jakarta and Bangkok, passive cooling can be extended up to 7% of annual hours using high thermal mass with night flushed ventilation in the tropical weather of Mandalay due to its diurnal temperature variation (Zune, 2021, Zune et al., 2020b). Hence, shading, thermal mass, and night-purge ventilation were considered as passive design strategies in this study that would also benefit future climate change conditions in the tropics.

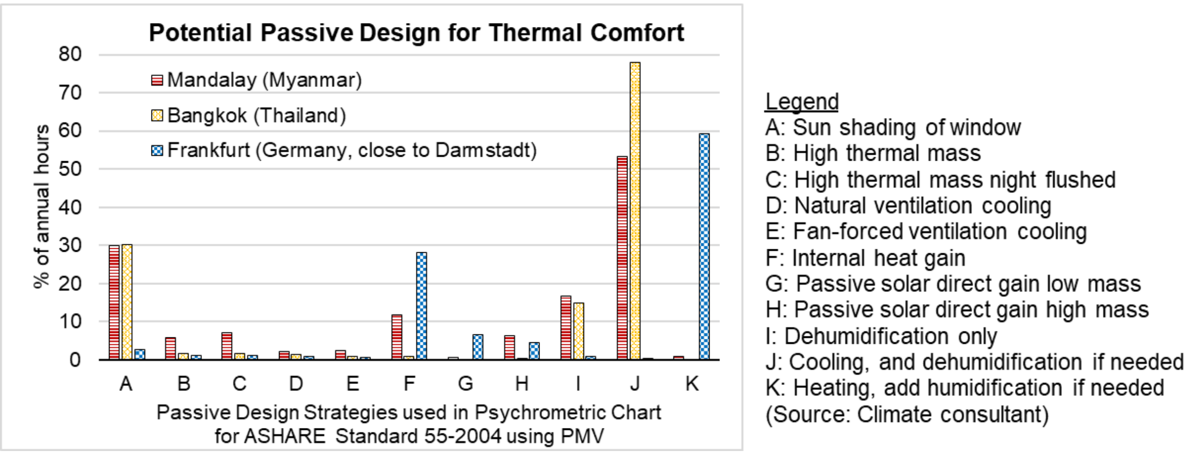


Figure 1. Comparison of potential passive design strategies for Myanmar, Thailand and Germany, based on the Psychrometric studies using ASHRAE standard 55-2004.

Finally, using the IESVE simulation tool, which is certified by the CIBSE system of model classification, we investigated the synergistic effects between shading and Passivhaus thermal building envelope that identify unresolved issues of the Passivhaus envelope in a tropical climate. This simulation exercise aimed to compare the impacts of two parameters on building thermal performance, namely building material and temperature parameters (which do not have to affect the physical meaning of the building directly) and shading parameters (which have physical data). Whilst the PHPP presents its results in monthly and annual figures, the IESVE generates its results from daily figures of 24 hours for each design day (IESVE, 2015). Whilst the PHPP calculates the impacts of revealing shadings on the building thermal performance, those effects were not fully captured in the IESVE models. Many scholars also have used the IESVE for the Passivhaus research with a focus on thermal analysis and shading design (McLeod et al., 2013, Aldossary et al., 2017, Abu-Hijleh and Jaheen, 2019, Costanzo et al., 2020).

2.1 Simulating building thermal performance

Whereas the configurations of shading (e.g., an egg-crate shading device which is a combination of overhangs and fins devices) play a role to avoid direct radiant solar heat gain from various angles (A.Al-Tamimi and SyedFadzil, 2011), the conditions of indoor thermal environments (i.e., ventilated and unventilated conditions) influence the extent of sensible heat flow paths of a building. If only natural ventilation is considered in a building with a Passivhaus building envelope, the building is in a purely free-running mode for passive cooling. In this case, the indoor thermal performance in a building is affected by the thermal properties of building envelopes (particularly from the thermal capacity for thermal mass and insulation), ventilation (including infiltration), occupants, and other auxiliary loads. The stored heat in thermal mass is emitted with some delay; therefore, a building with high thermal mass needs night-purge ventilation to cool and discharge accumulated heat from the mass for the next day. The results of decrement delay and differences between peak external and internal temperatures can be found in the hourly times series for different days. Despite the locations of thermal mass and its correspondence, shading would be critical in the tropical climates due to its requirements to prevent high solar heat gain on the surface of thermal mass; those aspects are not able to define in the PHPP clearly. Furthermore, a synthetically generated hourly time series is also not fully captured in the results of PHPP; therefore, critical differences between typical and extreme values can lead to systematic deviations if the effects of thermal mass and natural ventilation are considered in a building with Passivhaus building envelope.

The room height is suggested as 2.5m by default for a residential building to calculate the ventilated interior air volume in the PHPP; it is because the PHPP considers a building height from the whole dwelling level, rather than from individual rooms. As the building height can affect the ventilation volume for pre-heating and cooling air, the PHPP highlights to use of the actual building height for non-residential buildings. The typologies of a roof, i.e., flat roof or gable roof with no ceiling, could also affect the calculation of internal air volume for mechanical calculation. On the other hand, it has been highlighted that a Passivhaus building should consider overheating in individual rooms, rather than at the whole-dwelling level because different rooms of one dwelling can be faced overheating differently (Mitchell and Natarajan, 2019). Based on the review presented in this section, we further investigated the impacts of shading on the Passivhaus building envelopes for the tropical contexts using IESVE dynamic simulation.

2.2 Study models

Investigating the synergistic effects between external shading, Passivhaus U-values, and ventilation design entails a wide scope of work and contains a tremendous number of parameters. Understanding the sensitivity of the parameters (and their variables) is important in decision making and considerations for a variety of alternatives to enable comparison and optimisation methods. Each building plan and built form have both advantages and disadvantages; it must therefore determine which configurations have the most pronounced impact on building performance. Using an actual building as a sample would have been beneficial for decision making, because of its practicality and reality; however, to date, there are no Passivhaus design experiments in the Myanmar context. A simplified (surrogate) meta-model was thus used in simulation exercises for an appropriate study region within Myanmar to trial the Passivhaus approach in tropical climate contexts. One benefit of using a simplified model is that the potential impact of selected variables and their interaction can be understood easily, and can deconflict a certain degree of abstraction (Eisenhower et al., 2012).

For a timber building in Myanmar, room span and column spacing often come with 9 feet (2.7metre) as the market timber size comes with 18 feet (5.4 metres). Therefore, square building plans are often found as 18x18 feet or 27x27 feet, and rectangle building plans are often found as 18x27 feet or 27x36 feet. In this study, a small building plan with 18x18 feet was considered, but the values in the metric unit were considered as 5x5 metres. Therefore, all simulation models used in this study were proposed the same sizes: 5m length, 5m width, and 4m height. Each model had a south-facing glazed window and an east-facing door; therefore, the glazing was not directly affected by high afternoon ambient temperatures. Five model groups – A, B, C, D and E (Figure 2) - were defined according to the roof forms and roof extensions. The gable roof was aligned in a north-south direction and had 1.5m in height. Therefore, the model groups A, B, and C had an external surface area of 130m^2 each; the model groups D and E had an external surface of 141.6m^2 each; all models had the same treated floor area (TFA). In all models, the door had 1.2m in width and 2.2m in height; the window had 2.2m in width and 1.8m in height.

In this study, the model groups were further sub-divided by six shading scenarios, namely: (1) no shading, (2) internal shading with roller blind, (3) 0.5m width window overhang, (4) 1m width window overhang, (5) 0.5m width window overhang with internal roller blind shading, and (6) 1m width window overhang with internal roller blind shading. In sum, there were using 30 models (Figure 2) for this study. For the internal shading device, it was considered that there was no insulation property on the internal blind which was applied on the window during the daytime with a shading coefficient of 0.5 and short-wave radiant fraction 0.3 for Venetian blind.

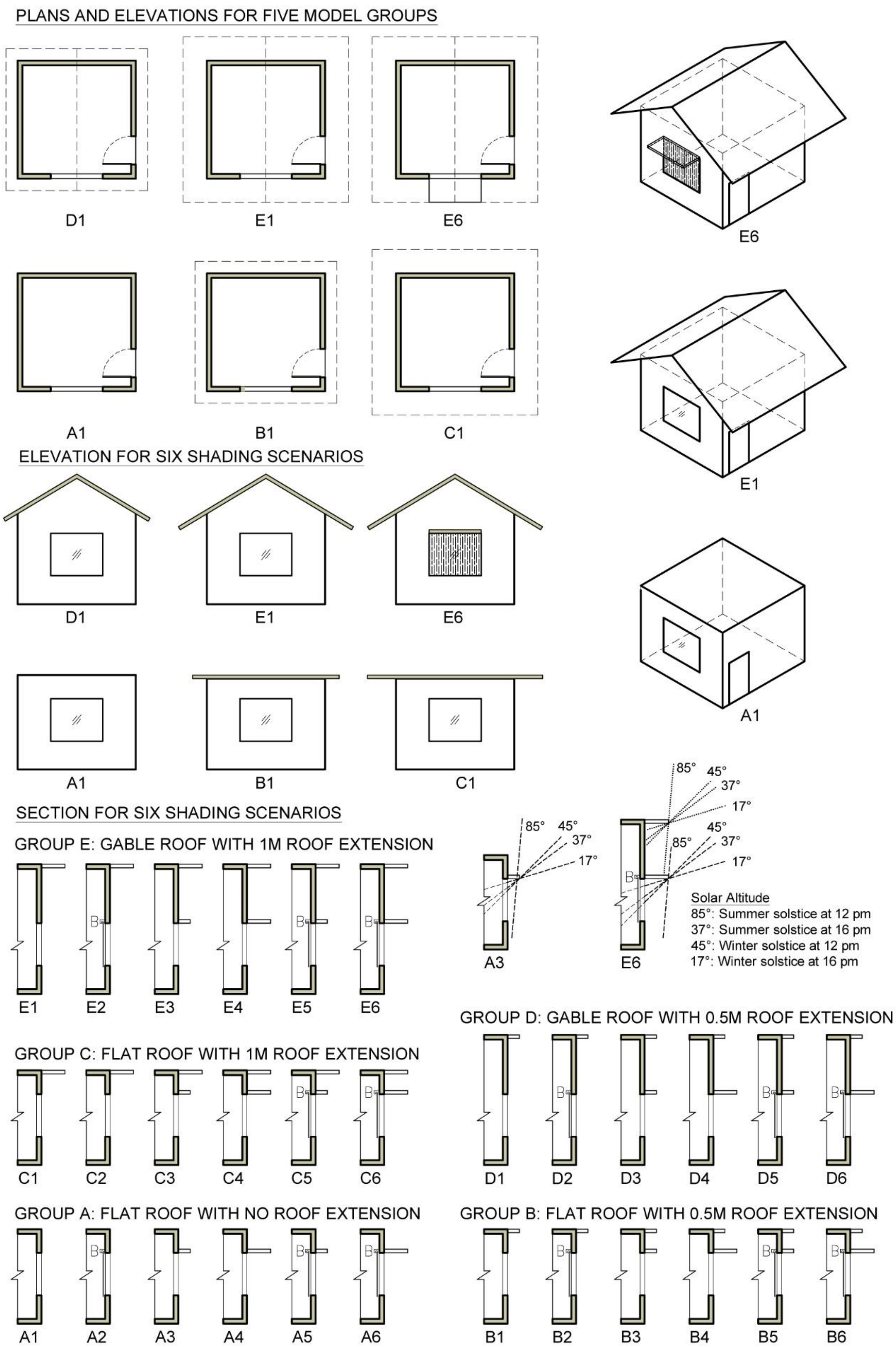


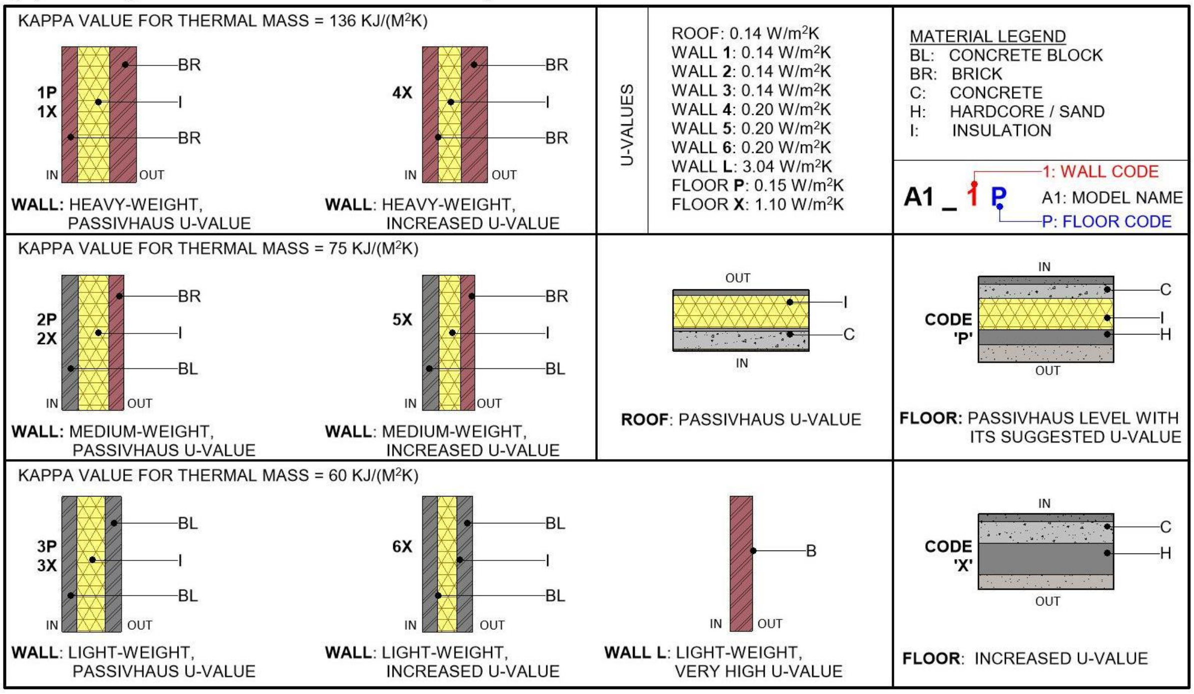
Figure 2. Example plans, elevations, and isometric models of the simulation models with different shading types on the south elevation

Three materials sets were proposed to investigate in the simulation study, namely-

I. Passivhaus building envelope configurations (full compliance with Passivhaus U-values),
II. partial Passivhaus building envelope configurations (compliance with Passivhaus U-values for wall and roof, but increased U-value for the floor,
III. Non-Passivhaus building envelope configurations (not complying with Passivhaus U-values in walls and floor as their U-values were slightly increased, but compliance with Passivhaus U-values for the roof).

Each building envelope configuration was then subdivided into three different thermal mass types (heavy-weight, medium-weight, and lightweight). Also, a very lightweight but a higher U-value wall type, which is a common 4.5 inches thickness brick wall type in Myanmar, was considered. The construction materials of the simulation matrix (Figure 3) were roughly selected based on the available material in Myanmar to differentiate the U-values between the Passivhaus level and the increased U-value of the partial Passivhaus level. A study based on Myanmar climates (Zune et al., 2018b) showed that if the roof has low solar absorptivity and high thermal emissivity "the higher the u-value, the better" could overwrite “the lower the u-value, the better.” Although the impacts of solar absorptivity on highly insulated walls and roofs are negligible, their effects would be significant with greater U-values of lightweight building envelope components used in this study. Moisture comes from the monsoon weather is a crucial food for the growth of algae and moulds; therefore, many Myanmar houses tend to choose a medium colour to protect the colour changes from a pure light colour envelope. Therefore, in order to represent a typical Myanmar house, a mid-range of solar absorptance values was considered. Glazed windows are the main area of building heat loss and heat gain than other parts of a building; the Passivhaus standard thus addresses with a high-performance window with low U-values but suggests using a high solar heat gain coefficient (SHGC) for solar heat gain demand in cold climates. For tropical climates, solar heat gain is undesirable. Typical Passivhaus is recommended a g-value higher than 50% in milder climates as solar gains are desirable in winter (Feist et al., 2019). For brevity of this study, the SHGC, a lower g-value of 0.37 was considered in all models. In sum, using three materials sets with three thermal mass types, there were ten building envelope scenarios with a range of thermal properties for this study, as shown in Figure 3 and Table 2.

(a) Building materail code used in this study



(b) Ten different building envelope configurations and code number (example for Model A1)

I. Passivhaus building envelope configurations		
i	**A1_1P**	: Model A1 with Heavy-weight Passivhaus wall and Passivhaus floor
ii	**A1_2P**	: Model A1 with Medium-weight Passivhaus wall and Passivhaus floor
iii	**A1_3P**	: Model A1 with Light-weight Passivhaus wall and Passivhaus floor
II. Partial Passivhaus building envelope configurations		
iv	**A1_1X**	: Model A1 with Heavy-weight Passivhaus wall and increased U-value for floor
v	**A1_2X**	: Model A1 with Medium-weight Passivhaus wall and increased U-value for floor
vi	**A1_3X**	: Model A1 with Light-weight Passivhaus wall and increased U-value for floor
III. Non-Passivhaus building envelope configurations		
vii	**A1_4X**	: Model A1 with Heavy-weight increased U-value for wall and increased U-value for floor
viii	**A1_5X**	: Model A1 with Medium-weight increased U-value for wall and increased U-value for floor
ix	**A1_6X**	: Model A1 with Light-weight increased U-value for wall and increased U-value for floor
x	**A1_LX**	: Model A1 with Light-weight high U-value for wall and increased U-value for floor
Note: Similar naming systems to be applied to other model groups.		

Figure 3. Simulation codes based on model name and building material codes

Table 2. Building envelope configuration used in this study (CIBSE, 2015, IESVE, 2015)

Building envelope configuration	U-value (W/(m²K))	Kappa value for thermal mass (kJ/(m²K))	Mass (kg/m²)	Solar absorptance	Thickness (mm)
Roof					
Comply with Passivhaus U-value	0.14	95	306	0.55	385
Wall					
1. Heavy-weight, Passivhaus U	0.14	136	489	0.5	500
2. Medium-weight, Passivhaus U	0.14	75	258	0.5	415
3. Lightweight, Passivhaus U	0.14	60	130	0.5	400
4. Heavy-weight, Increased U	0.20	136	489	0.5	440
5. Medium-weight, Increased U	0.20	75	266	0.5	355
6. Lightweight, Increased U	0.20	60	130	0.5	340
L. Lightweight brick wall, not complying with Passivhaus U-values.	3.04	60	255	0.5	150
Floor					
P. Comply with Passivhaus U-value	0.15	174	780	0.55	580
X. Increased U-value	1.11	400	812	0.55	400
Window					
Comply with Passivhaus U-value	Net U = 1.25, U (glass only) = 0.75, g-value = 0.37*.				
Door					
Comply with Passivhaus U-value	Net U = 0.8				

2.3 Calculation and simulation cases

Internal heat gain, ventilation profiles, and weather scenarios were first defined. In this study, the internal (sensible) heat gain was set as 2.1 W/m^2 as a continuous profile, which is based on the PHPP suggestion of the range of 2.1 to 4.1 W/m^2 for a single-family home (Feist et al., 2019), considering the use of highly efficient appliances and lighting and low occupancy, as suggested by Passivhaus standard; however, the latent gain was not considered. The infiltration rate was set as 0.042 ACH in this study; this value results from a 50 Pa fan pressurization test result of 0.6 h^{-1} (air changes per hour) which is the highest air leakage rate permitted for Passivhaus buildings (Feist et al., 2019) and energetically effective air exchange rate of 0.072 h^{-1}; however, it is important to note that this study was particularly focused on a free-running mode with natural ventilation. Therefore, the impacts of infiltration are hardly noticed. Window opening during the daytime is very common in Myanmar, regardless of lightweight or non-lightweight building types. Therefore, the impacts of different building envelope configurations on indoor air temperature were firstly checked for daytime ventilation by opening windows in all models from 06:00 to 18:00. Night-purge ventilation plays a critical role to cool, and discharge accumulated heat from the mass. Therefore, four window opening profiles – 24 hours open (including night-purge ventilation), 24 hours close, daytime open and daytime close – were introduced. The same simulation exercises were then repeated using three windows profiles to check the impacts of night-purge ventilation.

Simulation cases were generated using a typical weather file produced by Huang et al. (2014), which accounts for the years between 2005 to 2013. A historical weather file for the year 2019 and two future weather files produced by Zune et al. (2020d) were also used in this study. The future weather file-1 was based on a typical weather file that contained large diurnal temperature differences throughout the year. The future weather file-2 was based on recent weather data monitored in 2019, which contained small diurnal temperature differences throughout the year due to increased night-time temperatures in Myanmar. The NASA projections for mean annual and seasonal temperature change above the baseline (1980-2006) across Myanmar showed that the country is projected to warm by 1.3°C to 2.7°C in 2041-2070 (Horton et al., 2017, NASA, 2015). Whilst the exact temperature increment is unpredictable, adding a single estimate of expected annual change in air temperature consistently to the typical or historical weather files could provide useful estimates of heating and cooling demand (Cox et al., 2015). In this study, both future weather files were created by adding increased temperature values consistently to the typical and historical weather files; the method was referred to the use of a "shift" of a current hourly weather data parameter following the studies by (Jentsch et al., 2008). It is worth noting that CIBSE TM59 (2017) suggests using the design summer years (DSYS) for analysis of overheating, and it is good practice to take into account future weather files. Noted that this study used predicted summer temperatures which were higher than the other seasons. The NEX-GDDP dataset by NASA includes downscaled projections for Representative Concentration Pathway an intermediate scenario RCP 4.5 and a worst-case climate change scenarios RCP 8.5 from the 21 models and scenarios for which daily scenarios were produced and distributed under CMIP5 (Coupled Model Intercomparison Project Phase). As of July 2021, the Meteonorm data sets for Myanmar come without global radiation. Future weather files used in this study were further limited because parameters such as solar radiation, sky cover, relative humidity, wind, and precipitation were not changed in the future weather files due to limited available data sets. Despite predefined studied models and simulation inputs, other building parameters such as glazing ratio, external emissivity, and solar absorptance coefficients remained consistent in all simulation models. Table 3 presents a list of simulation matrices and simulation sets used in this study based on predefined scenarios.

Table 3 Simulation matrix used in this study

Scenarios	Count	Name of scenarios
Shading	30	Model A1 to E6
Building envelope materials	10	1P, 2P, 3P, 1X, 2X, 3X, 4X, 5X, 6X, LX
Window Opening	4	24 hours open, daytime open, daytime close, and 24 hours close
Weather files	4	typical, recent, and two future weather scenarios

Parameters	Description
Material properties	Table 2
Internal gains	2.1 W/m^2
Infiltration	0.042 ACH
Ventilation	Transient wind-driven ventilation from outdoor wind speed
Temperature setpoint	23.4°C (mean outdoor temperature of December and January when it was assumed the indoor temperature was closely reflected the weather outdoor in a free-running mode)

Simulation sets	Comparison and use of simulation scenarios
1. Shading scenarios	Comparisons of 30 models (Figure 2) in a daytime window opening scenario where the building envelope configurations were switched from 1P to LX.
2. Building envelope material configuration	Comparisons of 10 building envelope configurations (Figure 3 and Table 2) where 6 models (A1, A4, C1, C4, E1, E4) were simulated in a daytime window opening scenario.
3. Outdoor climate influences	Comparison of four different outdoor climates.
4. Extreme thermal discomfort	Consideration of future extreme outdoor temperatures in a naturally ventilated condition.
5. Window opening schedule effect	Consideration of the resultant effects of thermal mass and insulation using four window opening profiles.

3 Quantifying thermal comfort

The modern science of thermal comfort considers that thermal comfort is affected by a number of subjective perceptions and incidental activities relative to ambient air temperature, surrounding surface temperatures, humidity, and airflow rate parameters, which are collectively considered environmental parameters in objectively defining the thermal comfort range of a physical environment (Fanger, 1970). The ASHRAE and the BS EN ISO 7730:2005 (10) defined thermal comfort as a psychological phenomenon (Nicol et al., 2005) that shows *'that state of mind which expresses satisfaction with the thermal environment'* (ASHRAE, 2010, BSI, 2006).

Humans worldwide have the same essential physiology and a core temperature of around 36.5°C to 37.5°C, which is conceptualised as a thermodynamic machine in models to benchmark and maintain thermal comfort, regardless of great variety in human metabolism, activities, and cultural and climate differences (Roaf et al., 2005). The thermal sensation is also influenced by seasonal variations and outdoor weather; for instance, the summer temperature causes a higher core temperature and a greater decrease in body weight than winter (Nakayama et al., 2019). A study shows that the Asian groups consistently selected a personal cooling system (PCS) airflow temperature 5°C higher, leading to 1.9°C warmer microclimate temperatures close to the person's chest compared to the European groups; therefore, both the Chinese and the Japanese participants selected significantly warmer temperatures of the PCS than the white, middle-western- Europeans (Havenith et al., 2020). There is a scope of subjective and cultural influences in thermal comfort by differences in ethnicity, heat production/metabolism, and long-term thermal history.

Climate change has been described as 'the biggest global health threat of the 21st Century (Costello et al., 2009) as it causes different episodes of extremely hot or cold temperatures which are associated with increased mortality. A study which estimated the relative risks of mortality in 11 cities of Eastern United States in 1973–1994 shows that there is a strong association of the temperature-mortality relation with latitude, with a greater effect of colder temperatures on mortality risk in more-southern cities and of warmer temperatures in more-northern cities (Curriero et al., 2002). Furthermore, factors such as baseline health and nutrition status, access to health care, demographics, and ability to respond to extreme conditions are important to research estimating weather-related mortality impacts from climate change; the study in the United States is an example (Anderson and Bell, 2009). Short-term peaks in mortality are associated with heat waves (Nicol et al., 2005). During the 2003 European heatwave, many European countries reached record-breaking temperatures, including 41.1ºC in Auxerre (France), 45.2ºC in Seville (Spain), 46ºC in Sicily (Italy), 38.5ºC in Kent (United Kingdom), and 48°C in Amareleja (Portugal) (WMO, 2010), and resultant deaths across the continent exceeded 70,000 (Robine et al., 2008). Likewise, during the 2010 heatwave in Myanmar, the outdoor maximum air temperature reached 47.2°C in Myinmu, 46.5°C in Myingan, 45.7°C in Monywa, 45.5°C in Magway, 45°C in Mandalay, 44°C in Meiktila, and 42.5°C in Yangon (Phyu, 2010). As a result, more than 230 people died of heat-related illness as a consequence of the 2010 heatwave, a record from the health authorities of Mandalay (Nai, 2010). An observational study for people aged 65 to 74 shows that the mortality was lowest at 14.3-17.3°C in north Finland but at 22.7-25.7°C in Athens (Greece) (Keatinge et al., 2000). Therefore, weather–mortality relationships from one community may not be applicable in another, i.e., the contexts of American, Asian and European, although mortality risk increases with the intensity or duration of heatwaves.

Buildings are often designed using two methods in the judgment of thermal comfort - heat balance and adaptive methods – both in combination as a mixed-mode or hybrid model, in addition to considering factors influenced by cultural mechanisms, behavioural adjustments, and psychological adaptations. Using the heat balance method and an ‘active’ ventilation approach, the steady-state PHPP calculations are carried with a limited range of physical measures relating to space occupied and assumed clothing, occupancy, and activity level (Feist et al., 2019). In a heat balance model, thermal comfort is achieved if the body temperature can be held in a narrow range as skin moisture is low, and physiological effort of regulation is minimised. In this model, the building and equipment size are often designed considering an ultimate acceptable limit (e.g., peak temperature threshold). Hence, for mechanically ventilated buildings that have a heat balance model, using predicted mean vote (PMV), CIBSE defines the acceptable temperature ranges based on a narrow range of ±0.2K for a high level of the category I building, ±0.5K for a normal level of the category II building and ±0.7K for a model level of the category III building, where the category of the buildings is defined based on the applicability and level of expectancy (CIBSE TM52, 2013). Furthermore, the CIBSE recommends using 21°C to 25°C as an acceptable summer operative temperature range in dwellings (CIBSE, 2015). Unlike CIBSE, the PHI suggests that the frequency of overheating above 25°C should not exceed 10% of the occupied year in a Passivhaus building (Feist et al., 2019). If the frequency of overheating above 25°C is exceeded by 15% of the occupied year, the Passivhaus assessment considers this to be an unacceptable failure of performance (Hopfe and McLeod, 2015), whereas the best Passivhaus practices suggest keeping this value under 5% due to the prediction of occupant's behaviour in the cold European climates (Mitchell and Natarajan, 2019).

The implications of air movement and humidity are considered in the adaptive comfort method; therefore, a comfort zone of 2 to 3°C on either side of the optimum can be taken as acceptable limits (Nicol, 2004). The occupants in naturally ventilated buildings are thus often tolerant of a significantly wide range of temperatures based on a combination of behavioural adjustment and psychological adaptation (deDear and Brager, 1998). Hence, the values for acceptable temperature range and overheating thresholds for free-running buildings vary in different standards according to the building types and other factors. Unlike a heat-balance model, the acceptable temperature ranges for free-running buildings in the CIBSE buildings are ±2K, ±3K, and ±4K for the category I, II, and III buildings, respectively (CIBSE TM52, 2013). The CIBSE further suggests that the internal operative temperature (a combination of mean radiant temperatures and air temperatures) of a free-running building should not exceed 30°C (CIBSE, 2015, CIBSE TM52, 2013).

Until 2021, no research and assessments have provided the thermal threshold of both the heat balance and adaptive models for the Myanmar context. Singapore and Thailand countries are geographically close to Myanmar; therefore, they share similar vernacular house styles in the past for similar climates. In a modern case, field experiments in naturally ventilated buildings in Singapore (deDear et al., 1991) and the study of the thermal response for the Thai office environment (Busch, 1990) presents a good agreement of the thermal neutrality 28.5ºC for the internal operative temperature in the tropical climates, whereas culture context could affect thermal response. As the Passivhaus standard was initially developed using the heat balance method for a cold climate, 25°C limits of an overheating threshold would have been a question for a free-running building with a Passivhaus building envelope in the tropical climate. In Myanmar, the average daily high temperatures in the weather files of Mandalay were usually above 26°C throughout the year, and above 30°C in the summer. In Mandalay, annual relative humidity is usually above 40% (Zune et al., 2018a); therefore, above the air temperature 37°C with a relative humidity of 40% in shaded areas, a heat-index temperature is increased, then human health is threatened with increased risk of heat cramps, heat exhaustion, and heat stroke (National Weather Service, 2019). If the air temperature is above 40°C with a relative humidity of 40% to 50%, an extreme danger stage of heat stress could start. Hence, the indoor operative temperatures 30˚C, 36˚C and 40˚C were proposed in this study to check the simulation results generated for scenarios with free-running modes, considering the values of 30˚C and 36˚C could be likely appropriate benchmarks for the context of hot and humid climates; similar comparison method was used in the study of the vulnerability of homes to overheating in Myanmar (Zune et al., 2020d). Note that those values do not represent comfort benchmarks for Myanmar subjects in a free-running mode. For the steady-state PHPP calculation, due to the limited existing thermal comfort literature for Myanmar subjects, the overheating benchmark 25˚C was used in this study when it was compared to 19 cities from different countries, as presented below.

4 Shading in Passivhaus buildings

The shading reduction factors in the PHPP are particularly calculated from five elements: horizontal obstruction shading factor, vertical shading factor (e.g., the effect of window reveal), horizontal shading factor (e.g., balcony slab or lintel or overhang), additional shading elements (e.g., the effect of winter and summer), and temporary sun protection (e.g., the percentage of activation factor).

In this PHPP study, the world's first Passivhaus building was selected for a studied building. It was built with solid constructions and is oriented exactly towards the south and has 156m^2 of the TFA, 665m^3 of the enclosed volume, 184.3m^2 of the exterior walls, and 43.5m^2 of windows areas. Motorised external blinds are fitted for utilization as an easy-to-use temporary shading device, providing the possibility of free night-time ventilation in summer and passive solar gain in winter (Passipedia, 2019). Summer comfort is achieved by the high thermal mass of the building structure in combination with exterior Venetian blinds on the east and west façades (Schnieders et al., 2019). If all the design parameters of a building (i.e., geometry, material properties, building services, and benchmarks for heating and cooling demands) were fixed but the outdoor climates were varied, the impacts of the different climate contexts on the buildings could be checked. Therefore, a total of 19 cities across the world were selected to review the impacts of different climate contexts on the PHPP calculation. The impacts of shading design on a building were calculated in this exercise based on useful cooling demands and its frequency of overheating from its monthly and annual profiles.

A comparison of their average monthly temperature profiles and their Koppen climate classification is presented in Figure 5; the temperature data of 19 cities (Figure 4) was taken from the PHPP software; the temperature data of Myanmar was from ASHRAE (Huang et al., 2014). There were significantly higher monthly temperatures in Mandalay (Myanmar), Bangkok (Thailand), and Miami (USA) than in other cities.

As the building used for this exercise was designed with Passivhaus building envelope materials properties and shading for the climate of Darmstadt, understandably, when the outdoor climate data was switched from Darmstadt to other cities, the building was not meet the Passivhaus requirements of comfort and energy criteria. Therefore, the results of Figure 6a showed that both cooling demands and frequency of overheating were significantly increased in the warm-temperate climate cities (e.g., Madrid, Rome, and Lisbon); on top of that, the effects of horizontal and reveal shadings were more profound in the tropical and hot climates cities (e.g., Los Angeles, Miami, Brasilia, Manila, Bangkok, and Mandalay). Remarkably, in all cities, both cooling demands and frequency of overheating were slightly increased if the overhang shading were excluded and significantly increased if the temporary shadings were excluded - that showed the impacts of temporary shadings on the tested building. Even with all the shadings (horizontal obstruction shading factor, window reveal shading, overhang, and temporary shading), 90% overheating time of a year was found in Miami, Brasilia, Bangkok, and Mandalay due to the impacts of tropical and hot climate contexts (Figure 6b).

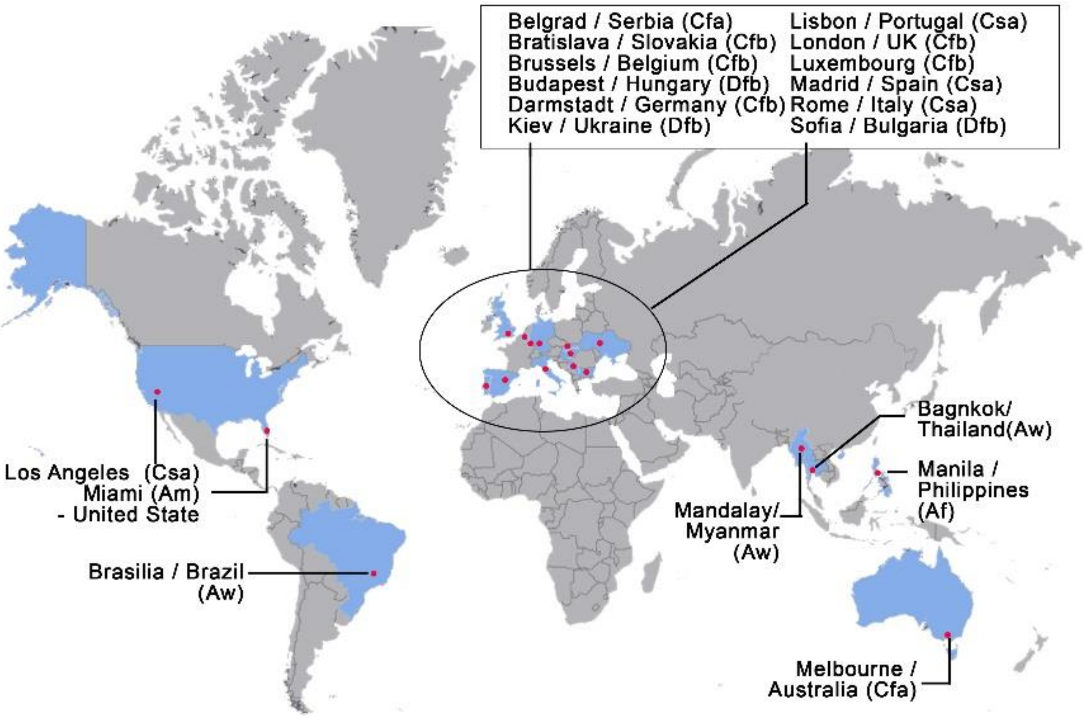


Figure 4 Location and Koppen climates of studied cities

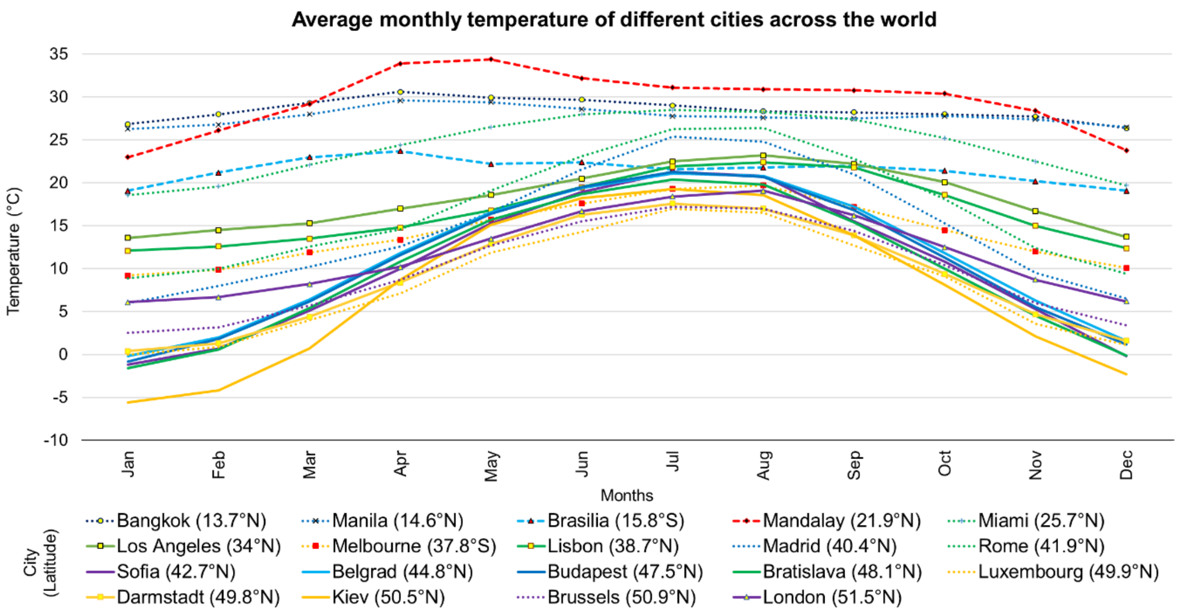


Figure 5. The average monthly temperature profile of 19 cities with their Koppen climate

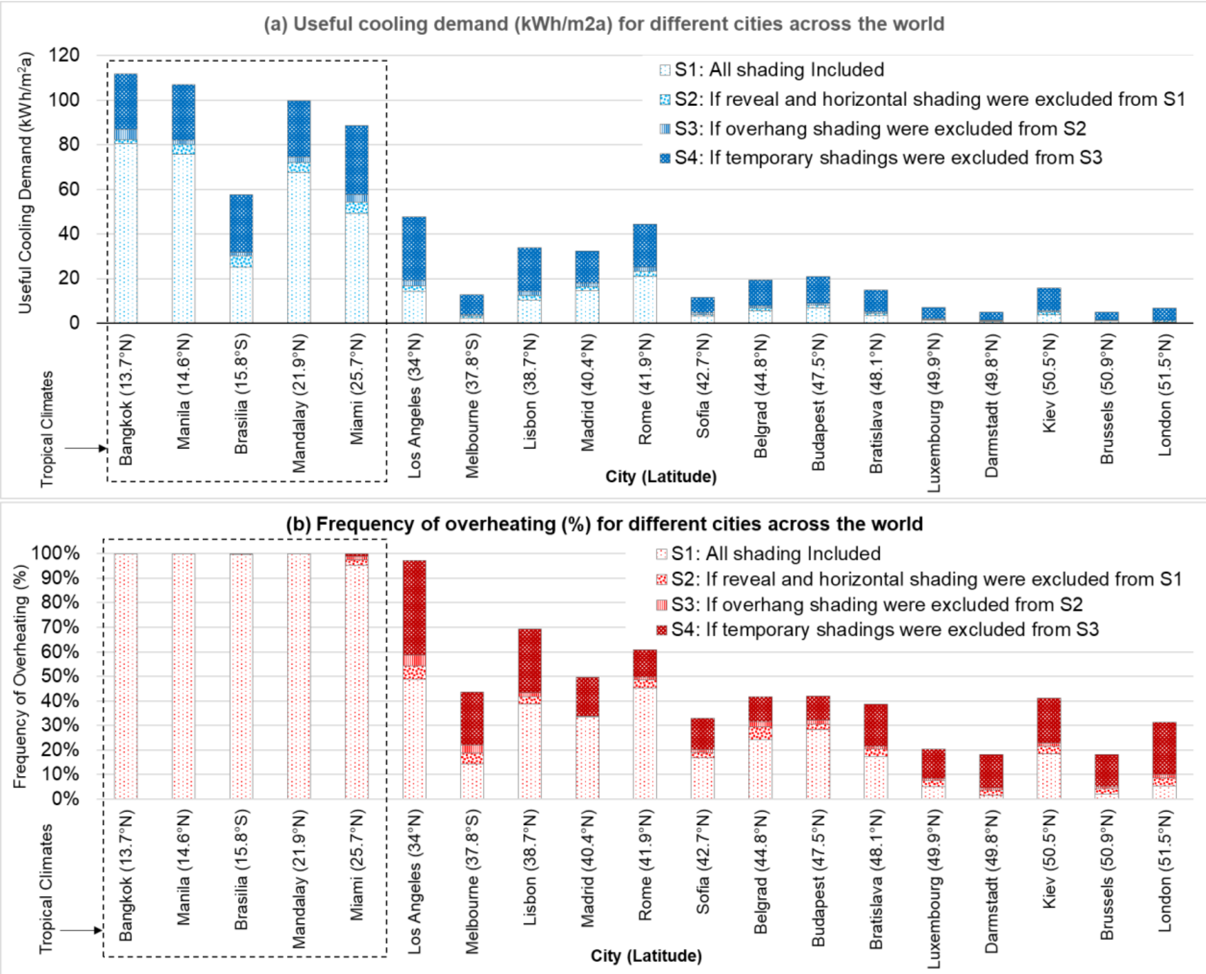


Figure 6. Annual useful cooling demand and frequency of overheating from the tested building located in 19 cities - PHPP shading calculation

It was found more than 80 kWh/m^2/year of space cooling load in Figure 6 for Miami, Bangkok, and Mandalay. The Bangkok Passivhaus, which is certified for a newly built dwelling, use cooling and dehumidification demand 88 kWh/m^2/year calculated according to PHPP (Passive House Database, 2020); therefore, it was an unsurprising result of Mandalay's tropical Myanmar climate. Calculating heat balance by modifying building envelope parameters (e.g., U-value), equipment size and performance, internal gain, etc, following the PHPP guide, would be necessary for further investigation. Despite the limitations discussed in this exercise, the results (Figure 6) revealed that there were significant impacts of outside climates and temporary shading on the tested building. The PHPP calculation provided in-depth details of shading calculation through different shading reduction factors; that shows a small amount but noticeable results in Figure 6 (see S2: if reveal and horizontal shading were excluded from S1).

Figure 6 revealed that the Passivhaus standard could be applicable in the Myanmar climate following its steady-state calculation with mechanical ventilation; on the other hand, it is necessary to solve significant cooling load requirements and overheating problems.

5 Dynamic simulation results

The results were presented for five simulation sets.

5.1 Shading scenarios

In order to check which model scenario performed better than others, Figure 7 compared the impacts of 30 models by generating their results for a "daytime window opening scenario" where the building envelope configurations were switched from 1P to LX - the code 1P represented the heavy-weight Passivhaus U-value wall and Passivhaus U-value for the floor; the code LX represented light-weight walls with a higher U-value. The models with building envelope configuration 1P maintained a high mean air temperature (i.e., 35°C to 40°C), but the temperature of about 40°C was not found in scenario 1P. The models with building envelope configuration LX maintained a long period of the temperature range between 25°C to 30°C, but about 10 hours were found above 40°C. That highlighted that the Passivhaus building envelopes with heavyweight walls were effective to offset the peak outdoor temperature, whereas a drawback of a high mean temperature was found throughout a year compared to the building envelope with lightweight, higher U-value walls. Whereas the results were not significantly different, Figure 7 showed that the annual hours below 30°C could extend in the models with building envelope configuration 1P by adding shading devices in the Passivhaus building envelope.

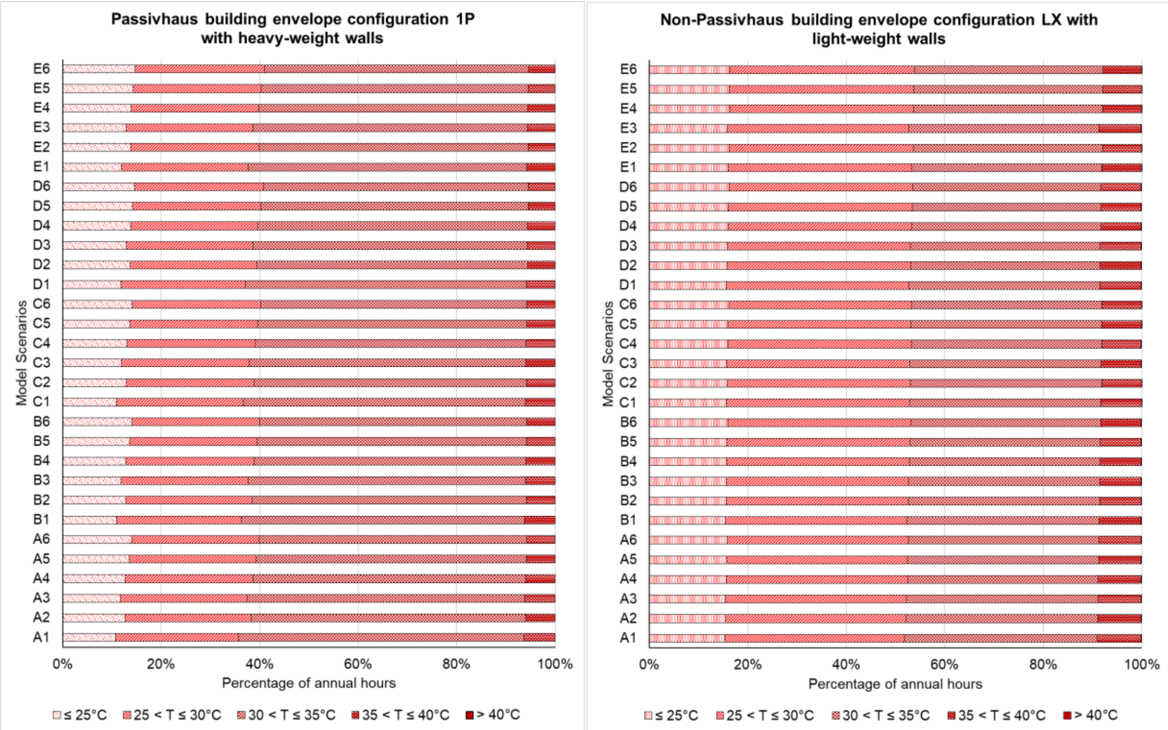


Figure 7. Temperature range found in 30 model scenarios, presented for building envelope configuration 1P and LX for a typical weather year, daytime window opening scenario

5.2 Building envelope material configuration

The impacts of different building envelope material scenarios on the indoor air temperature were compared in

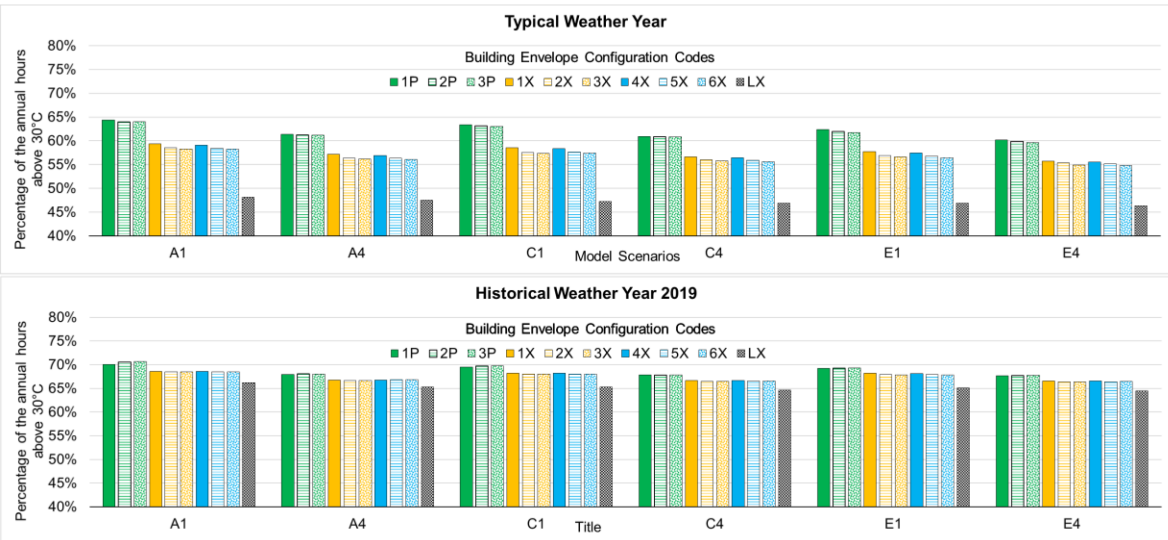


Figure 8. The thermal discomfort time of a year and the impact of the two different outdoor climates were compared using 30°C as a benchmark. Within the same model group - for

instance, models A1, A2, A3, A4, A5, and A6 - the results were varied according to ten building envelope configurations, rather than differences in building typologies and shadings. However, the impacts of building typologies and shadings were found when model A6 was compared to models C6 and E6. Therefore, the percentage of annual hours above 30°C was significantly reduced in model E6 compared to model A1 (

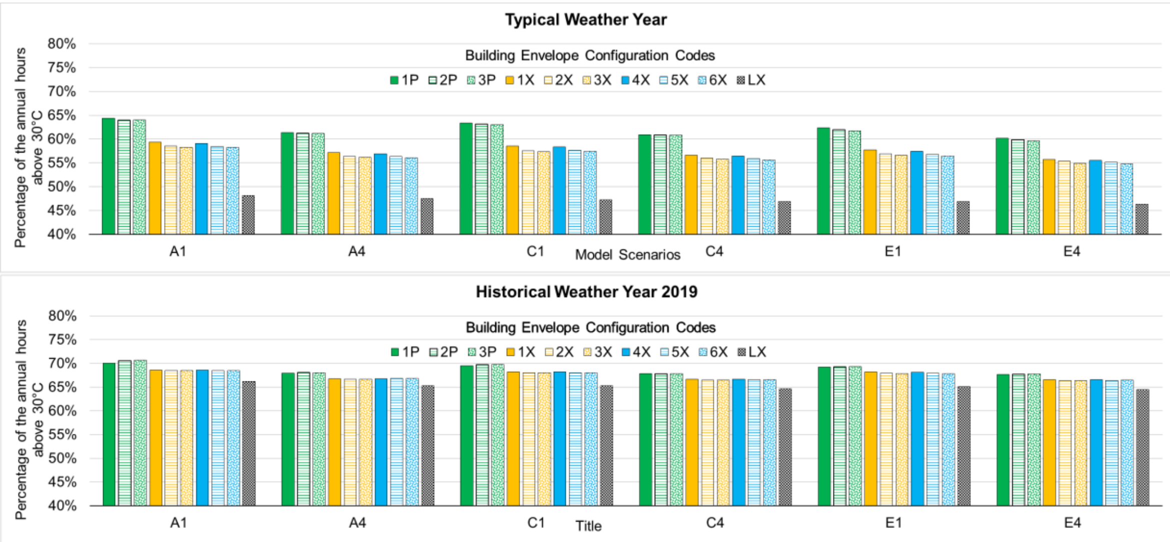


Figure 8). The reduction of 3.5% from models A1 to C4 was due to the positive results of a roof extension and window overhang. The reduction of 4.1% from the models A1 to E4 was found due to the results of building height. The building envelope configuration LX showed the best scenario if the indoor temperature was checked with 30°C benchmarks if the intensities of overheating high temperatures were neglected.

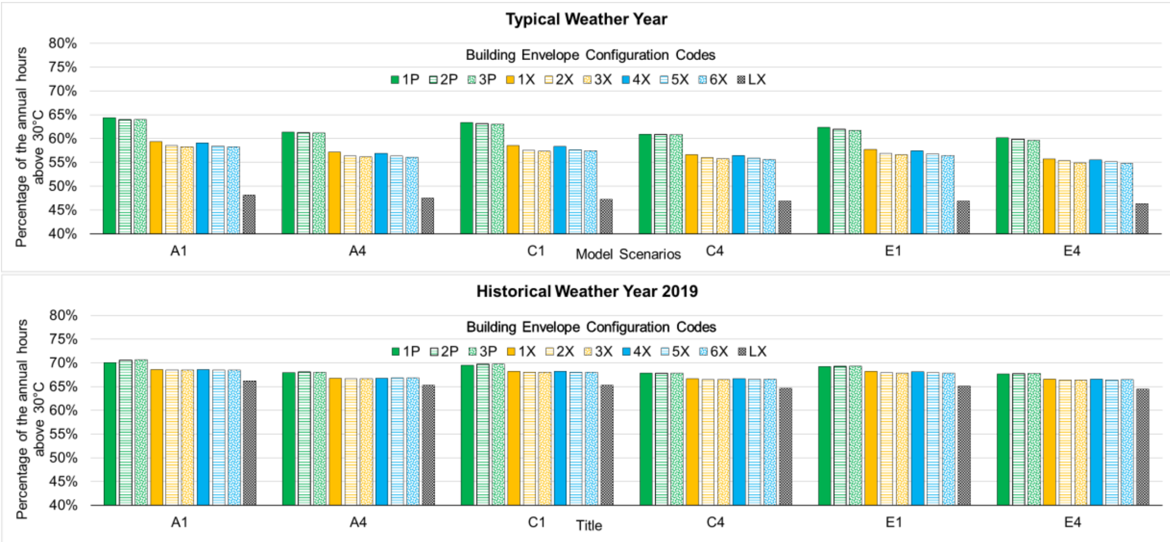


Figure 8. Percentage of a year above indoor air temperature 30°C in model group A for 10 building envelope configurations, presented for a typical weather year and historical weather year 2019 (P: Passivhaus level with its suggested U-value; X: Variation in Passivhaus levels with increased U-value), daytime window opening scenario

5.3 Outdoor climate influences

Figure 9 clearly showed that overheating hours could increase in future if only a free-running mode was considered by using four outdoor weather files. The results, which are shown in

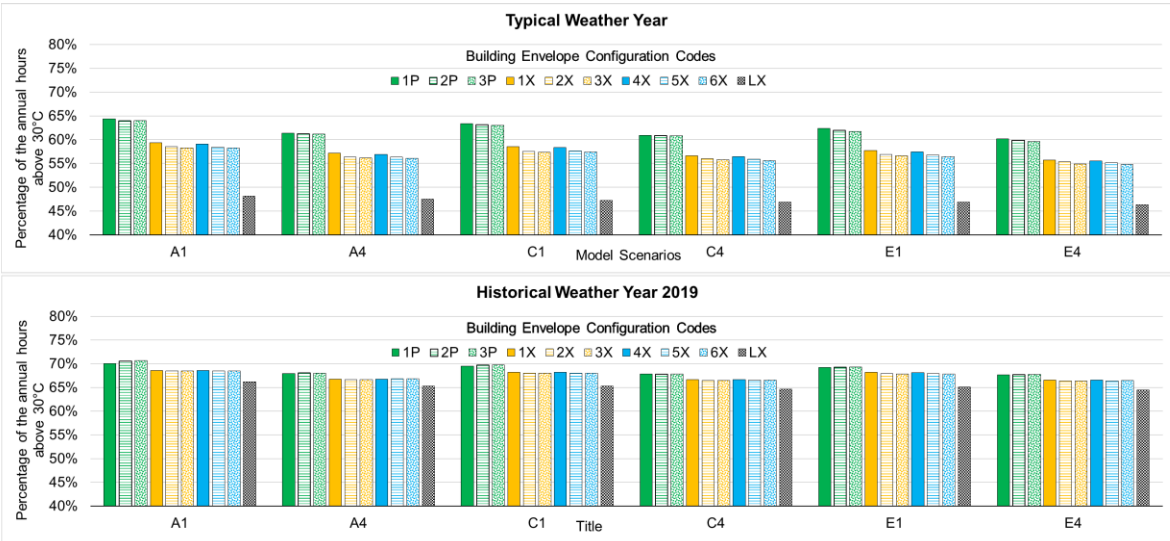


Figure 8 and Figure 9, indicate that model A1 gained the highest percentage of the annual hours above 36°C, while model E6 gained the lowest percentage in all ten building envelope configurations. The models with 1m roof extension and 1m width window overhang with internal roller blind shading (B6, C6, D6, E6) received a lower percentage of a year above 36°C than the models with no shading. Model A2 performed slightly better than the models A1, A3, and A4, and the same results were found in other model groups that showed the effectiveness of internal shading. The results showed that model E1 performed slightly better than C1, whereas the models C1 and E1 had the same TFA with different building heights. Unlike the results of

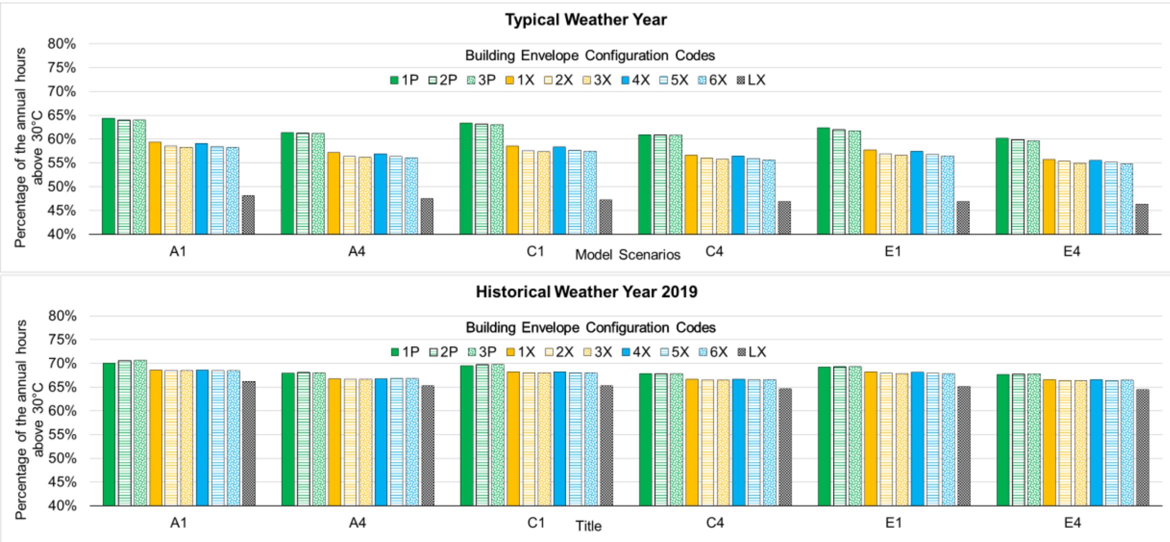


Figure 8, it was found that the models with building envelope configurations LX gained the highest percentage of the annual hours above 36°C than the models with other building envelope scenarios. If the models were assigned slightly higher U-values of walls and floors (scenarios 1X, 2X, 3X, 4X, 5X, 6X) than Passivhaus suggested, they received fewer annual hours above AT 36°C than the models with building envelope configurations 1P, 2P, and 3P.

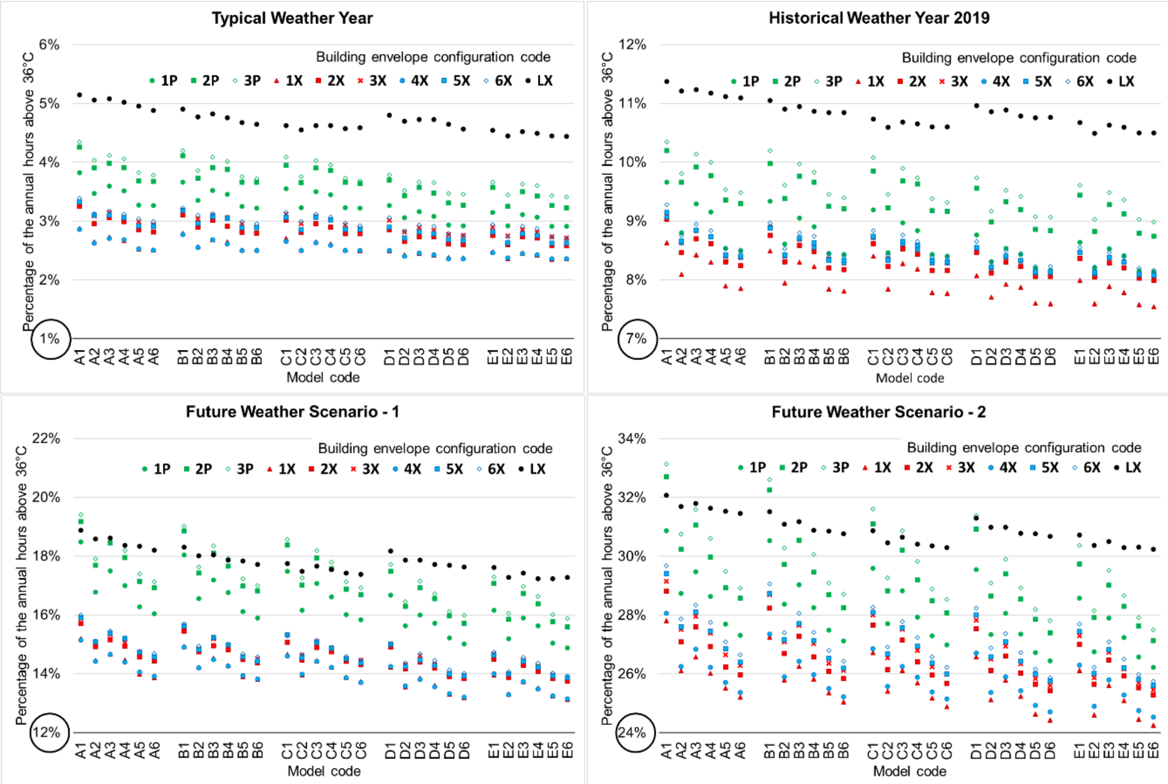


Figure 9. Percentage of a year above indoor air temperature 36°C in 30 models with 10 building envelope configurations, presented for a typical weather year, historical weather year 2019, and two future weather scenarios of Mandalay, daytime window opening scenario

5.4 Extreme thermal discomfort

Indoor air temperature 40°C was used as a benchmark to check the impacts of extreme thermal discomfort for the two future weather scenarios (Figure 10). The results (

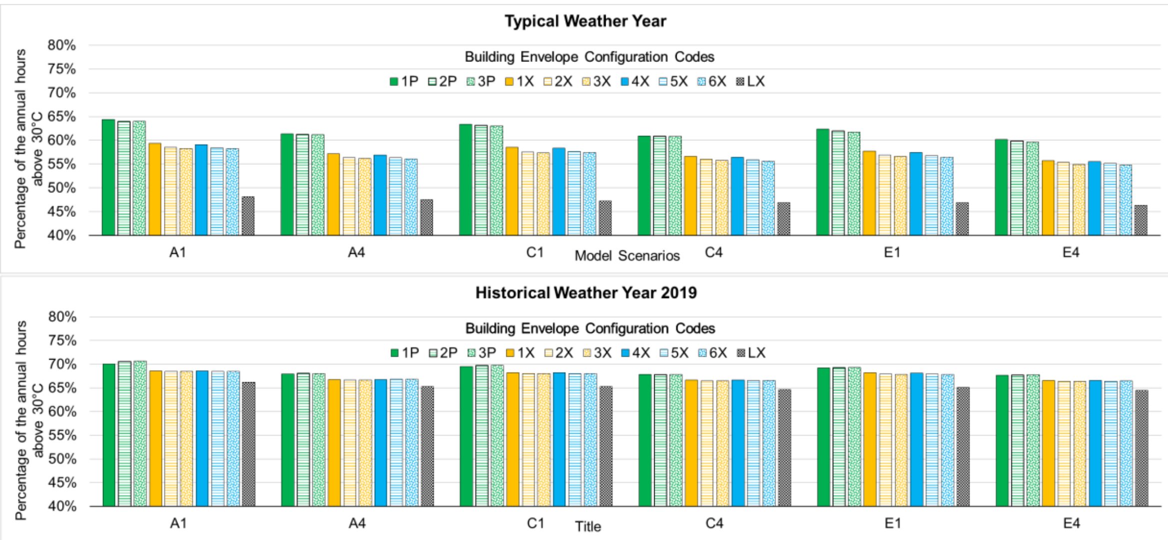


Figure 8, Figure 9, and Figure 10) showed that the models with building envelope configurations 1X, 2X, and 3X received a lower percentage of the annual hours above 36°C and 40°C than the other models. Similar results were found in the models with building envelope configurations 4X, 5X, and 6X, compared to the models with building envelope configurations 1X, 2X, and 3X. Therefore, the models with slightly higher U-values in walls and floors performed better than the models with Passivhaus strict U-values. For instance, for 36°C benchmarks, in the models, D6 and E6, 6.26% and 5.98% of annual hours can be reduced by adopting a Passivhaus envelope (1X) instead of a typical one (LX).

The comparison of the results of two future weather scenarios showed that reducing the insulation on the floors was more sensitive in the future weather scenario-2. Note that the future weather scenario-2 contained higher night-time temperatures than scenario-1. In Figure 9, for the model A1 with building envelope configuration 1P scenario, the annual hours above 36°C were increased eight times in the future weather scenario-2 (3.82% of annual hours) against typical weather scenario (30.88% of annual hours). Figure 10, which was generated using 40°C benchmarks for comparison, shows that the models with building envelope configurations LX received the highest percentage of annual hours above 40°C. That was significantly higher than the outdoor condition, due to its poor U-value of the wall while windows were opened only during daytime.

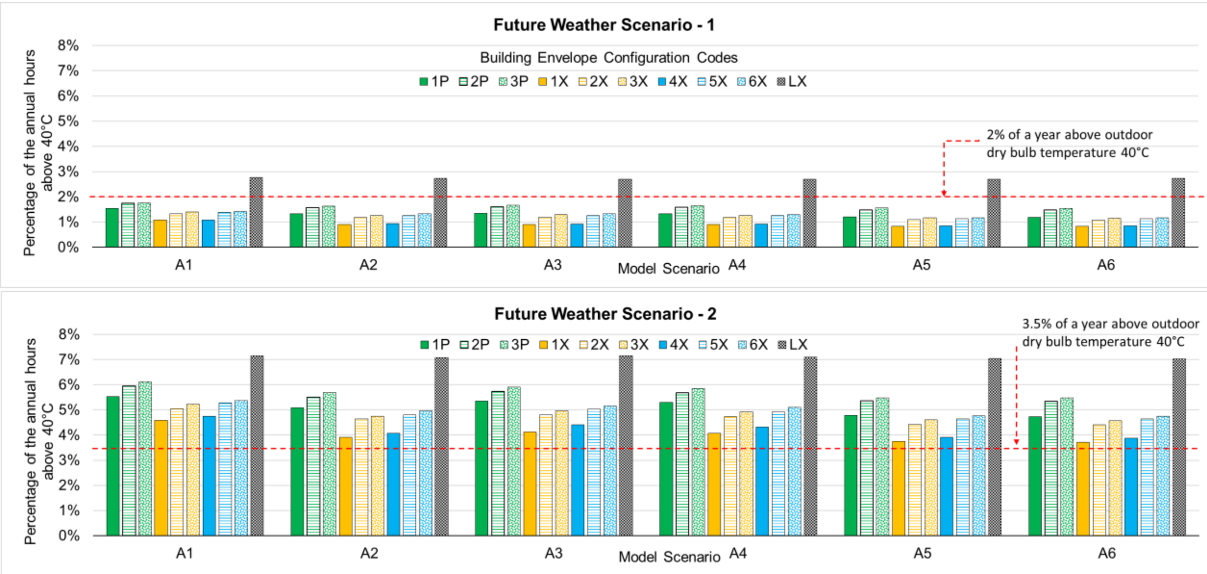


Figure 10. Percentage of a year above indoor air temperature 40°C in model group A with 10 building envelope configurations, presented for two future weather scenarios of Mandalay, daytime window opening scenario

Annual regression plots of the models A1, C6, and E6 for the building configurations 1P, 3P, 1X, 4X, and LX were presented in Figure 11 based on their daily hours in the future weather scenario-2, to compare their differences in the U-values of wall and floors. The best scenario was found in model E6 with building configurations 1X and 4X, proving the hypothesis was true. The worst scenario was found in the results of model A1 with building configuration LX. The results of Figure 11 revealed that a slightly higher U-value for walls and floors than the Passivhaus' suggestion of U-value could be more effective to offset high exterior temperatures for the studied climate in a free-running mode.

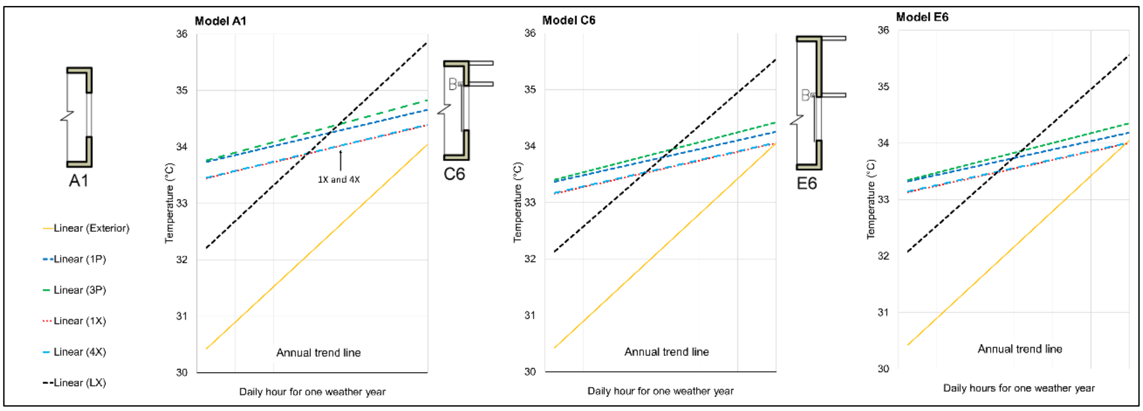
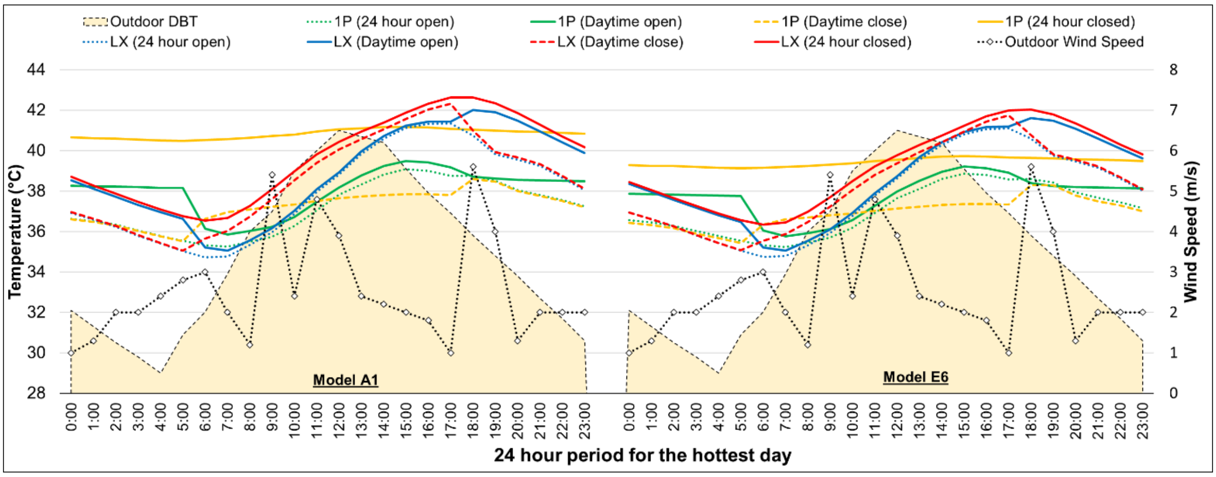


Figure 11. Annual regression plots for models A1, C6 and E6 for future weather scenario-2, presented for different building envelope configuration scenarios

5.5 Window opening schedule effect

Hourly temperature profiles are an important figure to check the performance of thermal mass. As the window opening has a significant impact on indoor thermal comfort, the effect of “four opening scenarios for windows” was checked by repeating the same simulation exercises. Figure 12 illustrates the 24-hour profile of indoor air temperature showing two building envelope configurations (1P and LX) for the models A1 and E6, compared with the outdoor dry bulb temperature for the historical weather year 2019. It was found that the models with building envelope configuration LX reached the highest and lowest temperatures in the hot and cold seasons, with a larger diurnal temperature swing due to its lack of less thermal mass property. The window opening scenario, closing continuously for 24 hours throughout the year, was the worst-case scenario; particularly this scenario caused significant temperature differences between models A1 and E6 in the cold season. On the contrary, the differences between the two models in two building envelope configurations were minimal on the hottest day.



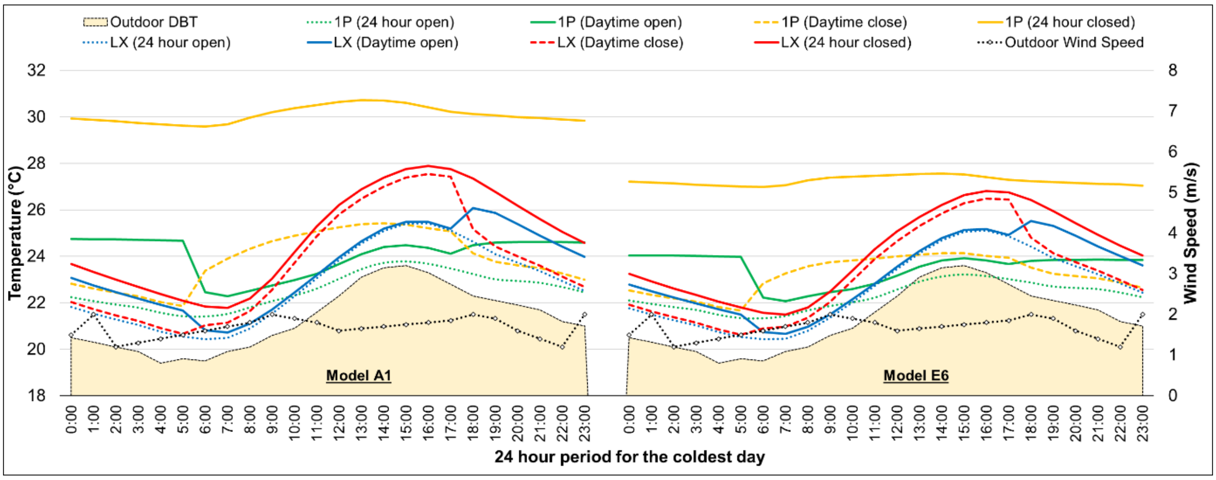


Figure 12. 24-hour profile of indoor air temperatures for the hottest and coldest days showing two building envelope configurations (1P and LX) for models A1 and E6, compared with the outdoor dry bulb temperature of the year 2019

On the hottest day, the outdoor temperature reached 32°C at midnight and 29°C at 04:00 but raised to 40.7°C at 13:00, and there was a high, turbulent wind speed profile, whereas the indoor air temperatures profiles were gentle (34.7°C lowest and 41.1°C highest) against the outdoor weather. If a model has a high thermal mass and insulation (scenario 1P), closing the window in the daytime had the advantage to reduce ventilation heat gain on the hottest day; however, a daytime opening window was preferable for the coldest day while mechanical ventilation was applied in the presented models. By switching building envelope configuration from LX to 1P, overall extremes of temperature were reduced by more than 2.4K in a daytime window open scenario, 3.45K in a daytime window close scenario. Overall, the models with building envelope configuration 1P received slightly lower temperatures than building envelope configuration LX.

In Figure 13, the annual regression plots of the models A1, C6 and E6 for future weather scenario-2 showed that the positive effects of night-purge ventilation (i.e., 24 hours window open profiles). While the annual trend lines of building envelope configuration 1P were significantly varied, the results of LX for three window opening profiles were noticeably parallel to each other. The best scenario was found in model E6 with night-purge ventilation as the mean temperature of about 2°C can be reduced by switching building envelop from LX to 1P. The worst scenario was found in the results of the window close profile. The trend lines of the building envelope configuration 1P with 24 hours window open profiles showed that annual mean temperatures could significantly reduce by adding shading and applying night-purge ventilation (see green solid lines); that showed the effectiveness of shading with high thermal mass.

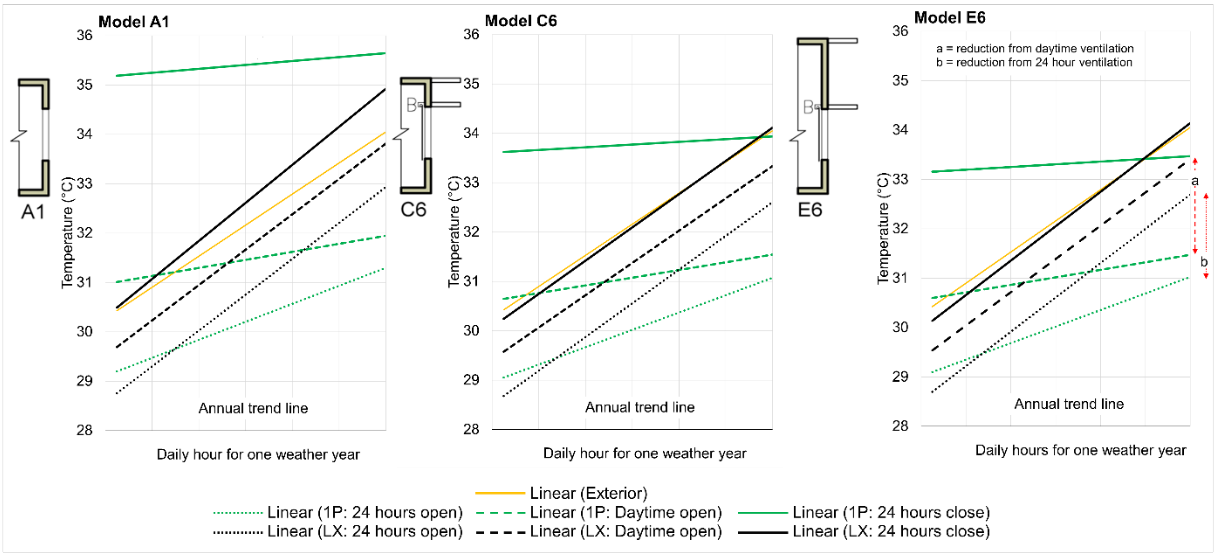


Figure 13. Annual regression plots for models A1, C6, and E6 for future weather scenario-2, presented for different window opening scenarios

When the windows of the models A1, C6, and E6 were open daytime only, it was found that the night temperature (minimum) was even higher than 36°C. As a result, it can be judged that mechanical ventilation will be required both for days and nights in the hottest months of the year if 36°C was considered for a mechanical set point. Despite the cold season, mechanical ventilation would be required in the daytime throughout the hot and wet seasons if windows were open daytime only. On the contrary, for model E6 in the future weather scenario-2, if night purge ventilation was considered, mechanical ventilation will be required in day time only throughout the hot and wet seasons. Overall, the regression plots with daily hours for the whole year showed the positive results of nigh-purge ventilation with high thermal mass, whereas it caused the expense of elevated mean temperatures.

6 Discussion

In this section, a discussion is presented considering the impacts of U-values, thermal mass, shading and ventilation on the five simulated sets.

Impacts of U-values: The simulation results revealed that the wall and floor types with slightly higher U-values (0.20W/(m^{2}K) for walls and 1.11 W/(m^{2}K) for a floor) than Passivhaus criteria performed better in the studied climate. Walls are generally the dominant component of the envelope; therefore, the effect of wall insulations was more obvious in

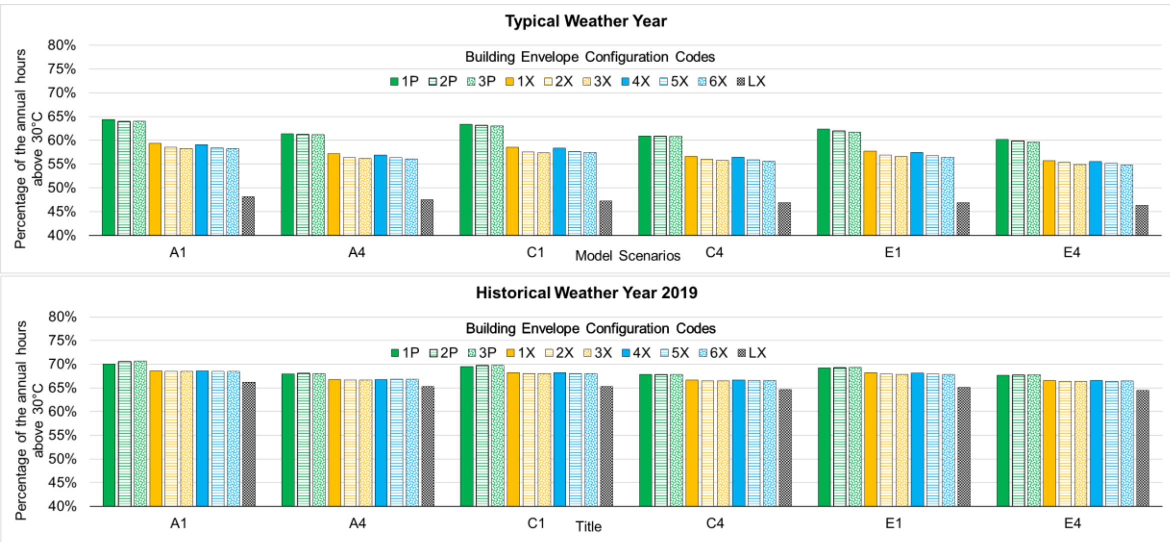


Figure 8, Figure 9, Figure 10, and Figure 11. Although a slightly higher U-value for walls and floors than the Passivhaus' suggestion of U-value can be more effective to offset high exterior temperatures for the studied climate in a free-running mode, building material selection from a range of U-values and thermal mass property could affect the length (Figure 10) and intensity of overheating time. As insulation and thermal mass are not common in Myanmar housing, a careful review is necessary for selecting slightly higher U-values for walls than the Passivhaus' suggestion (i.e., the building envelope configuration 1X, 2X, 3X, 4X, 5X, and 6X) for the future weather scenarios. For instance, Figure 3 showed thermal mass values were changed by switching brick walls (W1) to concrete block walls (W2); likewise, slightly thinner insulation thickness could significantly change the U-values of walls.

Impacts of thermal mass: The effectiveness of thermal mass and night-purge ventilation was found in the models with building envelope configuration 1P, although the thermal mass was less obvious with high-temperature benchmarks of 36°C and 40°C (Figure 9 and Figure 10) than with the results for the benchmark 30°C (

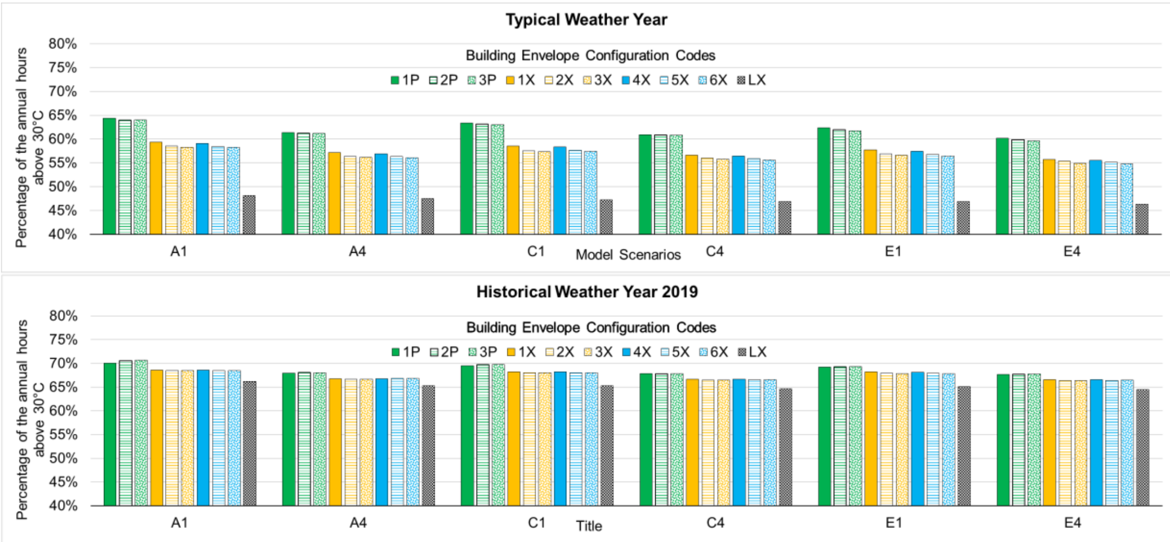


Figure 8). In Figure 10 for future weather scenario 2, it was found that 1% of the annual hours with a temperature above 40°C can be reduced by changing the thermal mass value from 60 kJ/(m^{2}K) to 136 kJ/(m^{2}K). Thermal mass properties in the highly insulated walls, while altering the internal temperatures by offsetting the decrement delay from the external peak temperature, were effective for acutely high temperatures. It also contributed to a high degree of annual and daily mean temperatures and caused the expense of elevated mean temperatures during normative conditions (Figure 12). Therefore, a careful examination needs to be worked on designing ventilation and selecting the building material for its thermal capacity and U-values in the studied climates.

Impacts of shading: Switching the model A1 to A6 by adding different shadings showed the sensitivity of shading in thermal performance. For the future weather scenario 2, Figure 9 showed that 0.6% of a year above 36°C can be reduced by adding 1m roof extension, window overhang, and internal shading in the model A1 if the building envelope configuration is in LX condition. In the same vein, 3.6% of the year above 36°C can be reduced by adding a 1m roof extension, window overhang, and internal shading in the model A1 if the building envelope configuration is in 1P condition. This revealed that 3.6% of annual hours in overheating time can be reduced by using shading with the high thermal mass Passivhaus building envelope. Visibly, the positive effects of shadings were more obvious when they were associated with the Passivhaus thermal envelope as shading offers to avoid solar heat gain absorption through the exterior surface of thermal mass. That suggests that it is essential to add shading for both walls and windows if a Passivhaus building in the tropic has a high thermal mass.

Impacts of ventilation: Whilst it was found that the positive results of nigh-purge ventilation with high thermal mass, it could cause the expense of elevated mean temperatures. In the free-running mode, a combination of Passivhaus building envelope and internal and external shadings was not able to maintain a temperature below 30°C for the studied climate. Hence, it could suggest that there was a need for a mix-mode ventilation strategy exclusively for the duration of the hot season to maintain thermal comfort. In the practices, all Passivhaus projects have been designed with an active ventilation application to provide building thermal comfort with low energy use. If the outdoor climate is extreme (i.e., very hot summer), closing the windows in critical times of the day when the outdoor temperature was very high would have perceived more benefit of the Passivhaus building envelope. If a building with Passivhaus building envelop is considered in a free-running mode, window opening profiles are crucial for improving their thermal condition. Future studies are required for all those considerations.

Mechanical ventilation requirements: The studied models and scenarios showed the effectiveness of reducing the maximum mean temperature of 2°C using heavy-weight Passivhaus construction (1P) against traditional building envelope (LX) in Myanmar climate, and there were positive results of coupling shading and night-purge ventilation (Figure 13). However, the studied models and scenarios also showed that it was impossible to provide thermal comfort through passive cooling alone. Therefore, the MVHR summer bypass could be an option to dissipate heat in tropical climates of Myanmar. Note that the use of MVHR could be omitted without compromising comfort levels, achieving at least equivalent energy savings resulting from adopting the Passivhaus model in climates with mild winters and cool summers (a mild maritime climate of the UK) (Sassi, 2013). This suggests that any ultra-low energy building model, Passivhaus, or naturally ventilated, will require some basic understanding to ensure optimal operation for ventilation. Particularly in the tropical climate, when active ventilation is introduced, removing the humid air is critical, for which integrating dehumidification into the MVHR will play a role in indoor thermal comfort. The ventilation system needs to include energy recovery to both pre-cool and dehumidify the supply air for the Passivhaus building for the hot-humid climates (Cotterell and Dadeby, 2012). Besides consideration for natural ventilation, one drawback of relying on mechanical ventilation for the peak summer temperatures is that the sizing of mechanical ventilation to cope with extreme weather conditions that occasionally occur. Furthermore, the comfort temperature benchmark could be different between the two thermal comfort models: adaptive and heat balance. Hence, future studies should explore a full package of Passivhaus for the tropical climate, both from natural ventilation and active ventilation design.

Limitation in building typology and material properties: The results of the present study were generated for a 5m x 5m square building plan. Smaller houses had significantly smaller ranges of energy efficiency ratings across eight orientations, in comparison to larger houses (Morrissey et al., 2011); therefore, the size of the building could affect the indoor thermal performance. A square building plan used in this study is a compact form that met the Passivhaus principle; however, further study will be required to analyse the impacts of aspect ratio. The aspect ratio is the ratio of a building's length to its width, which is an indicator of the general shape of a building. A long, narrow building can minimise the relative exposure of east and west surfaces, which is also more appropriate in the context of prevailing winds; therefore, a rectangular building plan is favoured as a passive design form for tropical climates (Hyde, 2001). In this study, a large surface area of the building envelope (the model E6) performed slightly better than others (e.g., the models with a flat roof) in a free-running mode, which was a contrast result compared to a Passivhaus building for the cold climate. There was a rough selection of construction materials (Figure 3); therefore, optimising building envelopment improvement for the Myanmar context will be a further study to explore cost-effectiveness, final energy consumption, material availability, and local skill sets. Nevertheless, this simulation exercise, together with the literature review, highlights that precise specifications on Passivhaus building envelope materials need to meet one specific boundary condition in one individual circumstance because climates differ despite the fact that energy use in Passivhaus buildings is measurable.

Limitation of dynamic simulations in a free-running mode: The Passivhaus standard is developed to achieve high thermal comfort with low energy consumption. Its fabric-first approach addresses to control heat transfer, infiltration, and leakage heat transmission, applying mechanical ventilation simultaneously. In this way, a Passivhaus building keeps the desirable thermal comfort consistently. This simulation study was only focused on limited thermal envelope parameters, exploring only three types of thermal mass properties and two types of floor material properties, to the hypothesis that a slightly higher U-value for wall and floor can be more effective in Myanmar climates than the very low U-value suggested by the Passivhaus standard. In this study, all those findings were based on a naturally ventilated condition; therefore, the Passivhaus suggestion of overheating benchmark 25°C was not used to compare the results. Further study is necessary to address the lack of overheating and thermal comfort benchmarks, and cooling related occupant behaviour analysis for a free-running mode for a Passivhaus building in the tropics, in terms of climatic elements and cultural factors. The results of the IESVE simulation were not able to generate detailed calculations for shading effects as the PHPP provides (Figure 6). It must be emphasized that the results of this study do not redefine the Passivhaus standard for the tropical climate context, rather this study fills the research gap of understanding the optimum Passivhaus envelope material properties for tropical climates when applying shading and natural ventilation. The study could be extended to the building envelope performance optimisation to minimise space cooling demand for the Passivhaus building in the tropic.

7 Conclusion

The impacts of shading design on a Passivhaus building in 19 cities for different climate contexts employing the PHPP steady-state calculation were firstly reviewed and evaluated in this study. The impacts of free-running mode on Passivhaus building envelopes were further investigated; for example, the impacts of thermal mass effect, the 24-hour temperature profile, and the percentage of annual hours for different temperature ranges. By using IESVE, Mandalay (Myanmar) was chosen as a case study location to test the hypothesis.

Different results of the 30 scenarios presented the synergistic effects between external shading and several building thermal envelope parameters. According to the findings of the simulation exercises, it can be suggested that the Passivhaus building envelope performed better to offset the outside peak air temperatures than the typical lightweight, not-insulated building envelope in the studied tropical climate. In the vernacular practices for the tropical climate, the indoor thermal environment of lightweight and high U-value walls is closely reflected in the weather outdoor; that also causes a high peak indoor air temperature. In contrast, this study showed that the advantages of insulation and thermal mass were found in the peak temperature condition (Figure 13) when it was compared to the high U-value building envelope with a lightweight wall. Besides the expense of elevated mean temperatures during normative conditions, the Passivhaus envelope is more advantageous in the tropics if there are extreme temperatures.

The results of this study revealed that a slightly higher U-value for walls and floors can be more effective for the tropical climate than the very low U-value suggested by the Passivhaus standard for the cold climate; this was tested in a naturally ventilated condition. The simulation results presented in this study agreed with Table 1. Following the Passivhaus standard, if some degree of thermal mass with insulated building envelopes is introduced into the tropical climate, protecting the solar gain is essential for a highly insulated building envelope; therefore, both walls and windows are required shading in the tropics. That underlined that knowledge of using external shading design must be expanded if the Passivhaus standard with high thermal mass walls is adopted in the tropical climate; that requires careful optimisation in selecting both the U-value and thermal capacity of the envelopes. Hence, an investigation of the synergistic effects between shading and building envelope design can make the implementation of Passivhaus more feasible for building cooling, as the costs with the envelope can be lower than the typical Passivhaus envelope.

The findings of this study were two folds: how the building thermal performance of Myanmar buildings can be strengthened by adopting the Passivhaus standard with extensive shading, and how the Passivhaus approach can bring both passive solutions through building fabric and potential hybrid ventilation. Hybrid ventilation is likely to be a solution to building cooling in summer for the emergence of heat and humidity in future climate change conditions in Myanmar. As the climates have changed, the use of shading with the Passivhaus approach, particularly using a mix-mode ventilation strategy exclusively for the duration of the hot season, can be a suitable adaptation strategy for Myanmar tropical climate buildings to avoid overheating and to maintain building cooling for a sustainable society. Enabling this to occur in tropical contexts, rather than adopting a single or a few Passivhaus components, the lessons learned from the literature and careful consideration of the building physics for one specific context must be holistically applied and tested.

References

A.Al-Tamimi, N. & SyedFadzil, S. F. (2011). The potential of shading devices for temperature reduction in high-rise residential buildings in the tropics. *Procedia Engineering,* 21**,** 273-282.

Abdulla, Z. & Rodrigues, L. (2016) The effect of shading, infiltration and ventilation levels on overheating and heating demands in UK residential buildings. Case study: Trent Basin Regeneration 36th International Conference on Passive and Low Energy Architecture (PLEA 2016), Cities, Buildings, People: Towards Regenerative Environments, 11-13 July Los Angeles, California, USA. 1371-1377.

Abu-Hijleh, B. & Jaheen, N. (2019). Energy and economic impact of the new Dubai municipality green building regulations and potential upgrades of the regulations. *Energy Strategy Reviews,* 24**,** 51-67.

Aflaki, A., Mahyuddin, N., Mahmoud, Z. A.-C. & Baharum, M. R. (2015). A review on natural ventilation applications through building facade components and ventilation openings in tropical climates. *Energy and Buildings,* 101**,** 153–162.

Aldossary, R. A., Rezgui, Y. & Kwan, A. (2017). Establishing domestic low energy consumption reference levels for Saudi Arabia and the wider Middle Eastern region. *Sustainable Cities and Society***,** 2017.

Anderson, B. G. & Bell, M. L. (2009). Weather-related mortality: How heat, cold, and heat waves affect mortality in the United States. *Epidemiology,* 20**,** 205-213.

ASHRAE (2010). Thermal environmental conditions for human occupancy. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Bere, J. (2013). *An introduction to passive house* London, RIBA Publishing.

Brien, W. O., Kapsis, K. & Athienitis, A. K. (2013). Manually-operated window shade patterns in office buildings: A critical review. *Building and Environment,* 60**,** 319-338.

Brumana, G., Franchini, G. & Perdichizzi, A. (2017). Design and performance prediction of an energy+ building in Dubai. *Energy Procedia* 126**,** 155-162.

BSI (2006). Ergonomics of the thermal environment: Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria London: British Standard Institute.

Busch, J. F. (1990). Thermal responses to the Thai office environment. *ASHRAE Transactions,* 96**,** 859-872.

CIBSE (2015). Environmental design 2015. Lavenham, Suffolk, UK: Chartered Institution of Building Services Engineers.

CIBSE (2017). Buildings for extreme environments: Tropical. *In:* Engineers, T. C. I. O. B. S. (ed.) *CIBSE Technical Memoranda.* Great Britain: The Lavenham Press.

CIBSE TM52 (2013). The limits of thermal comfort: Avoiding overheating in European buildings. Norwich, Norfolk: Chartered Institution of Building Services Engineers.

CIBSE TM59 (2017). Design methodology for the assessment of overheating risk in homes. *In:* Butcher, K. (ed.) *CIBSE Technical Memoranda.* London: The Chartered Institution of Building Services Engineers.

Costanzo, V., Fabbri, K. & Piraccini, S. (2018). Stressing the passive behaviour of a Passivhaus: An evidence-based scenario analysis for a Mediterranean case study. *Building and Environment,* 142**,** 265-277.

Costanzo, V., Gómez, J. E. C., Evola, G. & Marletta, L. (2020). Suitability of Passivhaus Design for Housing Projects in Colombia. *In:* Littlewood, J., Howlett, R. J., Capozzoli, A. & Jain, L. C. (eds.) *Sustainability in Energy and Buildings. Smart Innovation, Systems and Technologies.* Singapore: Springer.

Costello, A., Abbas, M., Allen, A., Ball, S., Bell, S., et al. (2009). Managing the health effects of climate change. *Lancet and University College London Institute for Global Health Commission,* 373**,** 1693-1733.

Cotterell, J. & Dadeby, A. (2012). *The Passivhaus Handbook: A practical guide to constructing and retrofitting buildings for ultra-low energy performance* UK, Green Books.

Cox, R. A., Drews, M., Rode, C. & Nielsen, S. B. (2015). Simple future weather files for estimating heating and cooling demand. *Building and Environment,* 83**,** 104-114.

Curriero, F. C., Heiner, K. S., Samet, J. M., Zeger, S. L., Strug, L. & Patz, J. A. (2002). Temperature and Mortality in 11 Cities of the Eastern United States. *American Journal of Epidemiology,* 155**,** 80-87.

deDear, R. J. & Brager, G. S. (1998). Developing an adaptive model of thermal comfort and preference. *ASHRAE Transactions,* 104**,** 145-167.

deDear, R. J., Leow, K. G. & Foo, S. C. (1991). Thermal comfort in the humid tropics: Field experiments in air-conditioned and naturally ventilated buildings in Singapore. *International Journal of Biometeorology,* 34**,** 259-265.

Eckstein, D., Kunzel, V., Schafer, L. & Winges, M. (2019). *Global climate risk index 2020. Who suffers most from extreme weather events? Weather-related loss events in 2018 and 1999 to 2018,* Bonn, Germany, Germanwatch e.V.

Eisenhower, B., Neill, Z. O., Narayanan, S., Fonoberov, V. A. & Mezić, I. (2012). A methodology for meta-model based optimization in building energy models. *Energy and Buildings,* 47**,** 292-301.

Eltaweel, A. & Su, Y. (2017). Parametric design and daylighting: A literature review. *Renewable and Sustainable Energy Reviews,* 73**,** 1086-1103.

Fanger, P. O. (1970). *Thermal comfort: analysis and applications in environmental engineering,* Copenhagen, Danish Technical Press.

Feist, W., Bastian, Z., Ebel, W., Gollwitzer, E., Grove-Smith, J., et al. (2019). *Passive house planning package (PHPP) version 9. [software].* Darmstadt, Passive House Institute.

Feist, W., Peper, S., Kah, O. & Oesen, M. v. (2005). *Climate neutral passive house estate in Hannover-Kronsberg: Construction and measurement results. PEP project information: no. 1,* Darmstadt, Passivhaus Institut.

Ferreira, J. & Pinheiro, M. (2011). In search of better energy performance in the Portuguese buildings—The case of the Portuguese regulation. *Energy Policy,* 39**,** 7666-7683.

Fiorito, F., Sauchelli, M., Arroyo, D., Pesenti, M., Imperador, M., Masera, G. & Ranzi, G. (2016). Shape morphing solar shadings: A review. *Renewable and Sustainable Energy Reviews,* 55**,** 863-884.

Gonzalo, R. & Valentin, R. (2014). *Passive house design: Planning and design of energy-efficient buildings,* Munich, Germany, Redaktion Detail, Institut für internationale Architektur-Dokumentation,.

Harmeling, S., Witting, M., Bals, C. & Kreft, S. (2011). *Global climate risk index 2011. Who suffers most from extreme weather events? Weather-related loss events in 2009 and 1990 to 2009,* www.germanwatch.org/cri, Germanwatch e.V.

Havenith, G., Griggsa, K., Qiu, Y., Dorman, L., Kulasekaran, V. & Hodder, S. (2020). Higher comfort temperature preferences for anthropometrically matched Chinese and Japanese versus white-western-middle-European individuals using a personal comfort / cooling system. *Building and Environment,* 183.

Hodgson, G. (2008). An introduction to PassivHaus: A guide for UK application. *In:* Establishment, B. R. (ed.) *IP 12/08.* Watford: IHS BRE.

Hooff, T. v., Blocken, B., Hensen, J. L. M. & Timmermans, H. J. P. (2014). On the predicted effectiveness of climate adaptation measures for residential buildings. *Building and Environment,* 82**,** 300-316.

Hopfe, C. J. & McLeod, R. S. (2015). *The Passivhaus designer's manual: A technical guide to low and zero energy buildings,* Oxon, New York, Routledge.
Horton, R., Mel, M. D., Peters, D., Lesk, C., Barlett, R., et al. (2017). Assessing the climate risks in Myanmar. A contribution to planning and decision-making in Myanmar: Technical report. New York, USA.
Huang, J. Y., Su, F. X., Seo, D. H. & Krarti, M. (2014). Development of 3,012 IWEC2 weather files for international locations (RP-1477). *ASHRAE Transactions,* 120**,** 340-355.
Hyde, R. (2001). *Climate responsive design: A study of buildings in moderate and hot humid climates,* London, Spon Press.
IESVE (2015). User Guide. https://help.iesve.com/: IES Virtual Environment.
iPHA. (2016). *The first Passive House: Interview with Dr Wolfgang Feist* [Online]. International Passive House Association. Available: https://blog.passivehouse-international.org/first-passive-house-wolfgang-feist/ [Accessed 14 April 2020].
James, M. & Bill, J. (2016). *Passive house in different climates: The path to net zero,* New York and Oxon, Routledge.
Jentsch, M. F., Bahaj, A. S. & James, P. A. B. (2008). Climate changes future-proofing of buildings: Generation and assessment of building simulation weather files. *Energy and Buildings,* 40**,** 2148-2168.
Keatinge, W. R., Donaldson, G. C., Cordioli, E., Martinelli, M., Kunst, A. E., Mackenbach, J. P., Nayha, S. & Vuor, I. (2000). Heat-related mortality in warm and cold regions of Europe: observational study. *BMJ,* 321.
Kottek, M., Jurgen, G., Beck, C., Rudolf, B. & Rubel, F. (2006). World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift,* 15**,** 259-263.
Lim, J. Y. (1987). *The traditional Malay house: Indigenous and traditional knowledge and practices*.
Limsakul, A. (2020). Trends in Thailand’s extreme temperature indices during 1955-2018 and their relationship with global mean temperature change. *Applied Environmental Research,* 42**,** 94-107.
Lomas, K. J. & Porritt, S. M. (2016). Overheating in buildings: lessons from research. *Building Research & Information,* 45**,** 1-18.
McLeod, R. S., Hopfe, C. J. & Kwan, A. (2013). An investigation into future performance and overheating risks in Passivhaus dwellings. *Building and Environment,* 70**,** 189-209.
Michler, A. (2015). *Hyperlocalization of architecture: Contemporary sustainable archetypes,* Los Angeles, eEvolo Press.
Mitchell, R. & Natarajan, S. (2019). Overheating risk in Passivhaus dwellings. *Building Services Engineering Research and Technology,* 40**,** 446-469.
Mlakar, J. & Strancar, J. (2011). Overheating in residential passive house: Solution strategies revealed and confirmed through data analysis and simulations. *Energy and Buildings* 43**,** 1443-1451.
Morrissey, J., Moore, T. & Horne, R. E. (2011). Affordable passive solar design in a temperate climate: An experiment in residential building orientation. *Renewable Energy,* 36**,** 568-577.
Nai, A. (2010). *Myanmar: Heatwave kills 230 in Mandalay (a report from Democratic Voice of Burma)* [Online]. Informing humanitarians worldwide. Available: https://reliefweb.int/report/myanmar/myanmar-heatwave-kills-230-mandalay [Accessed 13 November 2019].
Nakayama, A., Mitsui, T., Nakata, T., Mabuchi, H., Kawabata, K., et al. (2019). Changes in thermal comfort, core temperature, and body weight during simulated parcel home-delivery in summer and winter. *Industrial Health,* 57**,** 604-614.

NASA (2015). Mean temperature change (°C) projections and mean precipitation change (%) projections in the 2041-2070 period compared to the 1980-2005 average for Myanmar. *The image is created by using the data from NEX global daily downscaled climate projections 2015. Available from: https://nex.nasa.gov/nex/projects/1356/*

National Weather Service. (2019). *The heat index equation by Lans P. Rothfusz* [Online]. Weather Prediction Centre: National Weather Service. Available: https://www.wpc.ncep.noaa.gov/html/heatindex_equation.shtml [Accessed 8 August 2019].

Nicol, F., Rudge, J. & Kovats, S. (2005). Safe and warm; effect of climate change on thermal comfort and health. *In:* Roaf, S., Crichton, D. & Nicol, F. (eds.) *Adapting Buildings and Cities for Climate Change: A 21st-Century Survival Guide.* An imprint of Elsevier: Architectural Press.

Nicol, J. F. (2004). Adaptive thermal comfort standards in the hot-humid tropics. *Energy and Buildings,* 36**,** 628-637.

Oettl, F. (2012). "Green“ Austrian Embassy Jakarta. *16th International Passive House Conference (iPHA).* Hanover.

Osterreicher, D. & Sattler, S. (2018). Maintaining comfortable summertime indoor temperatures by means of passive design measures to mitigate the urban heat island effect: A sensitivity analysis for residential buildings in the city of Vienna *Urban Science,* 2.

Passipedia. (2018). *Example* [Online]. The Passive House Resource. Available: https://passipedia.org/examples [Accessed 28 December 2020].

Passipedia. (2019). *The Passive House in summer* [Online]. Passipedia » The Passive House Resource » Basics » The Passive House in summer. Available: https://www.passipedia.org/basics/summer?s[]=shading [Accessed 9 June 2020].

Passive House Database. (2020). *Passive house database* [Online]. Passive House Institute, the Passivhaus Dienstleistung GmbH, the IG Passivhaus Deutschland and the iPHA (International Passive House Association) and Affiliates. . Available: https://passivehouse-database.org/index.php [Accessed 10 April 2020].

Passive House Institute (2014). *Active for more comfort: passive house*, Germany, www.passivehouse-international.org, International Passive House Association, the Passive House Institute (PHI).

Passive House Institute. (2015). *Passive House requirements* [Online]. The Passive House Institute (PHI), Germany. Available: https://passivehouse.com/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm [Accessed 1 June 2017].

Passivhaus Trust. (2020). *What is Passivhaus* [Online]. The UK Passive House Organisation. Available: https://www.passivhaustrust.org.uk/what_is_passivhaus.php [Accessed 14 April 2020].

Phyu, A. S. (2010). *More heat records were broken in May: the Department of Meteorology and Hydrology (DMH)* [Online]. https://www.mmtimes.com: The Myanmar Times. [Accessed 27 December 2019].

Rahman, A. M. A. (2007). Housing design in relation to environmental comfort — a comparison of the traditional Malay house and modern housing. *Building Research & Information,* 22**,** 21-33.

Roaf, S., Crichton, D. & Nicol, F. (2005). *Adapting buildings and cities for climate change: A 21st-century survival guide,* An imprint of Elsevier, Architectural Press.

Robine, J.-M., Cheung, S. L. K., Roy, S. L., Oyen, H. V., Griffiths, C., Michel, J.-P. & Herrmann, F. R. (2008). Death toll exceeded 70,000 in Europe during the summer of 2003. *Comptes Rendus Biologies,* 331**,** 171-178.

Rodrigues, L., Sougkakis, V. & Gillott, M. (2016). Investigating the potential of adding thermal mass to mitigate overheating in a super-insulated low-energy timber house. *International Journal of Low-Carbon Technologies*, 11**,** 305-316.

Rodrigues, L. T. & Gillott, M. (2013). Climate resilience of a low-energy prototype house *Proceedings of the Institution of Civil Engineers - Engineering Sustainability,* 166**,** 337-350.

Sassi, P. (2013). A natural ventilation alternative to the Passivhaus standard for a mild maritime climate. *Buildings,* 3**,** 67-78.

Schiano-Phan, R., Ford, B., Gillott, M. & Rodrigues, L. (2008) The Passivhaus standard in the UK: Is it desirable? Is it achievable? , the 25th Conference on Passive & Low Energy Architecture, 22-24 October, Dublin, Ireland. PLEA 2008.

Schiano-Phan, R., Ford, B. & Zhongcheng, D. (2007). The Passivhaus standard in European warm climates: design guidelines for comfortable low energy homes, Passive-On IEE project. https://westminsterresearch.westminster.ac.uk/item/919zq/the-passivhaus-standard-in-european-warm-climates-design-guidelines-for-comfortable-low-energy-homes: http://www.passive-on.org/.

Schnieders, J., Eian, T. D., Filippi, M., Florez, J., Kaufmann, B., et al. (2019). Design and realisation of the Passive House concept in different climate zones. *Energy Efficiency*.

Schnieders, J., Feist, W. & Rongen, L. (2012). Characteristics of passive house implementations in different climate zones. *16th International Passive House Conference.* Hannover, Germany: International Passive House Associate.

Schnieders, J., Feist, W. & Rongen, L. (2015). Passive houses for different climate zones. *Energy and Buildings,* 105**,** 71-87.

Tran, D. N., Doan, V. Q., Nguyen, V. T., Khan, A., Thai, P. K., Cunrui, H., Chu, C., Schak, E. & Phung, D. (2020). Spatial patterns of health vulnerability to heatwaves in Vietnam. *International Journal of Biometeorology,* 64**,** 863-872.

Udrea, I. & Badescu, V. (2020). Usage of solar shading devices to improve the thermal comfort in summer in a Romanian PassivHaus. *Simulation: Transactions of the Society for Modeling and Simulation International,* 96**,** 471–486.

Valladares-Rendón, L. G., Schmid, G. & Lo, S.-L. (2017). Review on energy savings by solar control techniques and optimal building orientation for the strategic placement of façade shading systems. *Energy and Buildings,* 140**,** 458-479.

Wallemacq, P. & House, R. (2018). Economic losses, poverty and disasters 1998-2017. United Nations Office for Disaster Risk Reduction: Centre for Research on the Epidemiology of Disasters.

Watts, N., Amann, M., Arnell, N., Ayeb-Karlsson, S., Beagley, J., et al. (2021). The 2020 report of the Lancet Countdown on health and climate change: responding to converging crises. https://www.thelancet.com/action/showPdf?pii=S0140-6736%2820%2932290-X: The Lancet.

WMO. (2010). *European heatwave sets new temperature records* [Online]. https://public.wmo.int: World Metrological Organization. Available: https://public.wmo.int/en/media/news/european-heatwave-sets-new-temperature-records [Accessed 27 December 2019].

Yeh, S.-C. (2020). Bangkok first concrete passive house (Passivhaus). *The 24thInternational Passive House Conference* Virtual / Online.

Zune, M.(2021). *Improving the thermal performance and resilience of Myanmar housing in a changing climate.* PhD, University of Nottingham.

Zune, M., Rodrigues, L. T. & Gillott, M. (2018a) The resilience of natural ventilation techniques in Myanmar's vernacular housing. *In:* Ng, E., Fong, S. & Ren, C., eds.,

Passive and Low Energy Architecture Conference: Smart and Healthy within the 2-degree Limit, 10-12 December, Hong Kong. 513-518.
Zune, M., Rodrigues, L. T. & Gillott, M. (2018b) The sensitivity of roof surface and envelope insulation in naturally ventilated tropical housing: Case study across three climate zones in Myanmar. *In:* Riffat, S., Su, Y., Liu, D. & Zhang, Y., eds., 17th International Conference on Sustainable Energy Technologies, 21-23 August Wuhan, China. University of Nottingham & WSSET, 264-273.
Zune, M., Rodrigues, L. T. & Gillott, M. (2020a) The overheating risks in Myanmar vernacular dwellings: Indoor thermal environment study from measured and simulated data 35th PLEA Conference (Sustainable architecture and urban design: Planning post-carbon cities), 1-3 September, A Coruña, Spain.
Zune, M., Rodrigues, L. T. & Gillott, M. (2020b). A Review of Traditional Multistage Roofs Design and Performance in Vernacular Buildings in Myanmar. *Sustainable Cities and Society*, 60.
Zune, M., Rodrigues, L. T. & Gillott, M. (2020c). Vernacular passive design in Myanmar housing for thermal comfort. *Sustainable Cities and Society,* 54**,** -.
Zune, M., Rodrigues, L. T. & Gillott, M. (2020d). The vulnerability of homes to overheating in Myanmar today and in the future: A heat index analysis of measured and simulated data. *Energy and Buildings,* 223.