IMPROVING THE THERMAL PERFORMANCE AND RESILIENCE OF MYANMAR HOUSING IN A CHANGING CLIMATE

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to a girl who did not know about

a giant butterfly when she was young

but a narrative about her old days changes

the way she will decorate her little house.

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Image courtesy of Hkun Lat (permission obtained from the photographer)

This photograph displays a Buddhist temple occupying one half of a mountain, while the other has been entirely carved away by heavy machinery mining for jade, in Hpakant, Kachin State, Myanmar (Lat, 2021). The location of this picture is just 150km away from Myitkyina, one of the case study cities in this thesis. If a picture is worth a thousand words, this picture tells many unwritten stories of inequality, climate change, deforestation, complete disregard for human values in an unsustainable business-as-usual program, corruption, and never-ending civil wars of Myanmar: an unfinished nation at the heart of 21st century Asia, between India and China.

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Abstract

Despite the long-term climate risk index for the period 1990-2018, there is a dearth of research and understanding of the vulnerability of homes to overheating in Myanmar. This thesis adopted a “case study research method with multiple cases” and addressed concerns about climate change impacts on Myanmar housing, particularly for the thermal performance of detached houses, which comprise the primary housing type in Myanmar. In order to fill the research gap in Myanmar Sustainable Development Plan and the Myanmar Building Code, four objectives were structured for the scope of this thesis: (1) lessons learnt from Myanmar vernacular architecture; (2) an investigation of the impacts of climate change and overheating risks in Myanmar housing; (3) an investigation of the impacts of the Passivhaus’ fabric-first approach on the Myanmar contexts; and (4) a review of barriers, challenges, and limitations of adopting the Passivhaus’ fabric-first approach in Myanmar.

Changes in the use of building envelope materials were the focus of simulation case studies comparing vernacular materials and their customs in building modern materials; the results showed that vernacular houses would not be sufficient to achieve thermal comfort in the predicted future climate scenario RCP 8.5 as the efficacy of passive design techniques has decreased. The results of field case studies generated from a one-year-long monitored data set for a vernacular dwelling and a modern dwelling in Myanmar showed that both dwellings did not give an adequate performance to meet thermal comfort requirements throughout the year. The vernacular dwelling in the Koppen climate Cwa maintained wet-bulb temperature below 30°C when the outdoor weather had 8.5% of the annual hours above wet-bulb temperature 30°C. The modern dwelling in the Koppen climate Aw maintained 48.5% of the annual hour below wet-bulb temperature 30°C when its outdoor weather had 51% of the annual hour below wet-bulb temperature 30°C.

In order to determine the Passivhaus concept in an adaptive thermal comfort model of Myanmar housing, it was hypothesised that a slightly higher U-value for wall and floor could be more effective in Myanmar climates than the very

low U-value suggested by the Passivhaus standard; the simulation results revealed that the hypothesis could be sufficient to achieve Passivhaus targets if the synergistic effects between shading and building envelope design were considered. It was also found that if the roof has a cool roof effect, “the higher the u-value, the better” could overwrite “the lower the u-value, the better,” which is a characteristic of reflective insulation. Furthermore, it could meet the requirements to reduce building self-weight for the earthquake resistance design in Myanmar. However, it was also found that the Passivhaus scenario maintained a higher percentage of the annual hour for high heat index and wet-bulb temperatures than the partially Passivhaus scenario in the studied dwellings if no mechanical ventilation was considered.

The results of this research support the hypothesis, revealing that Passivhaus building envelope parameters and optimum variables can improve the tropical building thermal envelope of the studied climate in future climate change scenarios. Fabric-first variable case studies were particularly relevant given the vulnerability of homes to overheating in Myanmar, and the implications of the findings offer directions for more effective good practice and guidance for Passivhaus construction in Myanmar’s tropical context.

Personal context

I would like to take this opportunity to trace the personal context of this thesis. I was a BIM specialist, design engineer, and drafter, and those experiences asked me to see things from different perspectives. My first construction experience was a few Buddhist religious buildings and a bridge in 2007-2009, in my hometown - a small town in northern Myanmar, once the 5th-century Shan city of Sampanago, then the capital of the ancient state of Wanmaw, later part of the Shan kingdom in the 11th century, and today it is a town between two armed conflict zones in the 21st century. Growing up in a bookstore, listening to the story of old Bhamo, wondering the way my Dad's drawings changed to a building to live, were the strongest memories about the town.

My interest in building performance design was developed when I was working in Singapore in 2009-2017. Since 2010, I visited my home - just 190km away from one the case study town Myitkyina - every year, and I felt that the weather was not how I remembered it, but this passing thought did not trouble me as I stayed in my home for only a week before returning to Singapore. Whenever I visited my hometown from Singapore, I wondered the way the Myanmar landscape in my memories slowly changed and the way the buildings I used to see when I was young have consciously changed. When I decided to study for a PhD, one of my ex-colleagues suggested specialising in BIM and other digital construction technology, based on my BIM expertise over several years in Singapore. There was also increasing job market demand in this area from that time. I faced a surfeit of options.

I came to the University of Nottingham in 2017; my initial plan was to develop a low energy building design for Myanmar climates, based on the knowledge I gained in Singapore. In July 2018, I visited the NHS twice at midnight after the UK was hit by a heatwave, with temperatures exceeding 30°C for over 15 days in a row. That happened not only because of my heat and cold intolerance, but also because the building I lived in was not strong enough to provide natural ventilation and thermal comfort. Despite growing up and living and working in tropical weather for three decades, I was physically assaulted by a heatwave in the UK; what if I face high-temperature events frequently in the future?

Besides my interests in climate change impacts on building design, my experience of heat intolerance on my health gave me a renewed interest in building thermal performance design.

During my university days in Myanmar, around the 2000s, Dad taught me how to build a building conventionally, from a drawing to construction, until it is ready for clients to live in. There were a few projects that we built together, and we believed that we did our best and our clients were happy; now, I have my doubts about the thermal resilience of those buildings, and how far they can perform well in a changing climate condition. I am no longer sure what the most appropriate answer would be, but I have to acknowledge that my knowledge of the requirements of Myanmar buildings is somewhat limited, and the development behind the thesis is partly based on personal interests.

Strong childhood memories about my hometown, an interest in building performance design, and an unexpected health failure together galvanised my interest in building thermal performance design for a changing climate condition. The country I call home has been ranked second out of 183 countries in the long-term climate risk index since the 1990s. No one knows exactly how the future climate change and heave wave events will change the country.

The work of my thesis was generated from three perspectives. Firstly, I reviewed to see how housing has shaped in Myanmar, particularly from vernacular architecture. Then, I monitored how the housing in Myanmar thermally responded to the present climate, so I can see whether the thermal performance has been weakened for the required building thermal comfort or not. Finally, I investigated how the building thermal performance can be strengthened in future climate scenarios, for which, I compared the vernacular approach and the Passivhaus approach. The Passivhaus approach is a new concept for Myanmar. I wrote this thesis with the belief that Myanmar needs a new imaginative concept to prepare for the climate change emergency to come. That does not mean forgetting what we used to practice in vernacular architecture. There might be ways to bring technical excellence and vernacular beauty together.

The thesis was developed in 2016, just a year after the 2015 Myanmar general election, as a long period of isolation was officially ended. At the time of submitting this thesis, Myanmar is on the brink of state failure again, and the country remains ungovernable in 2021 after the military coup. No one could have imagined where Myanmar would still be in 2021. Therefore, I added the postscript to continue the research beyond this thesis.

When I decided to work in Singapore in 2009, and for this PhD in 2017, there were inexpressible losses and financial challenges. I could not be here without the support of my family and the care of my ex flatmates. One day, when my nephews and the children who shared the same roof with me in Singapore are at my current age, I hypothesise that they will think the financial risk I took was worth it.

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Whilst the past few years have been both challenging and fascinating, I could not have done this thesis without the encouragement, guidance, and support of a wonderful group of people. I feel indebted to them for their kindness, and I would like to express my deep gratitude to:

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- My two sisters, brother-in-law, Babagyi and Kyi Kyi Nwe, Kyi Kyi Aye and my cousins, for believing in my abilities, for long years of caring, unconditional love and financial support.
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It is difficult for me to thank every person who has given me the strength and inspiration to undertake this work and see it through. This thesis is a place I pause and see what I have learned. This amazing experience makes me believe that there is more to do in future, and I will enjoy doing what I love to.

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List of acronyms and nomenclature

ach	Air change per hour (unit: h^{-1})
AEC	The architecture, engineering and construction industry
AT	Air temperature
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
°C	degree Celsius
CEPHD	Certified Passivhaus Designers
CFD	Computational Fluid Dynamics
CIBSE	Chartered Institution of Building Services Engineers in the UK
CO_2	Carbon Dioxide
DBT	Dry-bulb temperature
°F	degree Fahrenheit
HT	Heat index temperature
IESVE	Integrated Environmental Solutions Virtual Environment software
IPCC	Intergovernmental Panel on Climate Change
MBE	Mean Bias Error
MDY	Mandalay (case study city)
MKN	Myitkyina (case study city)
MRT	Mean radiant temperature
MVHR	Mechanical ventilation with heat recovery
PH	Passivhaus
PHD	Passivhaus Database (https://passivehouse-database.org)
PHI	Passivhaus Institute in Germany
PHIUS	Passive Building Certification in North America
PHPP	Passive House Planning Package
RMSE	Root Mean Square Error
RH	Relative humidity
SA	External surface area (in PHPP calculation)
SA (α)	Solar absorptance
TE (ε)	Thermal emissivity
TFA	Treated floor area (in PHPP calculation)
WBT	Wet-bulb temperature
WWR	Window to wall ratio
U-value	Thermal transmittance
UHI	Urban heat island effect
UK	United Kingdom
YGN	Yangon (case study city)

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Burma is running out of time.

The country needs a radical agenda to fight inequality and prepare for the climate change emergency to come.

It needs a new story as well that embraces its diversity, celebrates its natural environment, and aspires to a new way of life.

Perhaps most of all,
Burma needs a new project of the imagination.

~ Thant Myint-U,
from The Hidden History of Burma, p258.

Figure 0-1. Myanmar in South-Asia Map [adapted from Bruce Jones Design Inc.2011 via http://www.freeusandworldmaps.com]

Introduction

Global warming trends are expected to continue throughout the remainder of the 21st century and beyond. The long-term effects of climate change include increased frequency and intensity of droughts, heat-related events (e.g. heat waves and bush fires), changes in precipitation patterns, stronger storms, intense solar radiation, and lengthened frost-free seasons (IPCC, 2014c). The Intergovernmental Panel on Climate Change (IPCC) reported that the warming trends, including higher extremes, are strongest over Asia, with increasing annual mean temperature trends at the country scale in East and South Asia observed throughout the 20th century (Hijioka et al., 2014). Across Southeast Asia, the temperature has been increasing at a rate of 0.14°C to 0.20°C per decade since the1960s, coupled with a rising number of hot days and warm nights, and a decline in cooler weather (Hijioka et al., 2014). Understandably, Asia is on the frontline of a changing climate; therefore, occupants and buildings in Asia will be increasingly vulnerable to climate risk without adaptation and mitigation.

Ensemble-mean changes in mean annual temperature are expected to exceed 2°C above the late 20th-century baseline over most land areas by the mid-21st century under RCP 8.5, and range from greater than 3°C over South and Southeast Asia to greater than 6°C over higher latitudes by the late 21st century. The ensemble-mean changes are less than 2°C above the late 20th-century baseline in both the mid-and late-21st century under RCP 2.6, except for changes between 2°C and 3°C over the highest latitudes. In South Asia, seasonal mean rainfall shows inter-decadal variability, and a noticeably declining trend with more frequent deficit monsoons under regional inhomogeneities; as a result, the frequency of heavy precipitation events is increasing, while light rain events are decreasing (Hijioka et al., 2014). The global long-term climate risk index, by Germanwatch[1], is an analysis based on

[1] Germanwatch is an independent non-profit, non-governmental organization, which is based in Bonn and Berlin and was founded in 1991. Its objective is to exert influence on public policy regarding environmental protection as well as relations between countries in the Global North and South. Germanwatch advocates for fair trade relations, responsible financial markets, obedience to human rights, and the prevention of dangerous climate change.

one of the most reliable data sets available on the impacts of extreme weather events and associated socio-economic data. The report of Germanwatch highlighted that Myanmar, at the heart of Southeast Asia, was ranked second out of 183 countries in the long-term climate risk index for the period 1990-2018 (Eckstein et al., 2019, Harmeling et al., 2011), and the rank has continued at the high risk.

Myanmar[2], formerly known as Burma, a peacock-shaped land on the world map, with a landscape scattered with gilded pagodas, home to 135 distinct ethnic groups for centuries. During the early 2010s, it had a democratic renaissance, after long years of military rule, and Myanmar was 'the toast of the world' (Myint-U, 2019, p1) politically, ending a long period of isolation of this culturally renowned land. Besides the changing dynamics of Myanmar politics, the country faces enormous development challenges in the midst of a rapidly changing and uncertain landscape, both in terms of politics and international aid (Bjarnegard, 2020). Among the enormous and multifaceted contemporary challenges of Myanmar in the late 2010s, one of the most formidable is the devastating impacts of climate change, which do not allow Myanmar to isolate politically, which should not be Myanmar's parts unknown (Bourdain, 2013). This thesis was developed in late 2015 based on the concerns of the climate change impacts on Myanmar, particularly for housing. In Myanmar, 70.4% of the population are found in rural areas (Ministry of Labour, 2015), and most buildings are detached houses. Even the urban area, multi-housing and high-rise are found in capital cities such as Yangon and Mandalay. This thesis was therefore mainly focused on detached house types, which have been commonly built in Myanmar.

The adverse effects of the earth's climate change, manifest in sudden extreme weather crises and slowly changing climatic conditions, have profound impacts on the health, comfort, and quality of our lives. The risk of overheating in

[2] Myanmma is the same word as 'Mien' the Chinese name and 'Man' the Shan name for Burma. The derivation from Brahma is on a level with the derivation of English from angels. The mediaeval scribes with the name Brahma before them write not Brahmadesa (land of Brahma) but Myammadesa (land of Myanmma), and an eleventh century Talaing inscription calls the Burmese 'Mirma'. [from Harvey, G. E. (1925) History of Burma, p3.]

buildings and the consequent impact on the occupiers' health 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; vulnerable populations were exposed to an additional 475 million heatwave events globally in 2019 (Watts et al., 2021). From 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). 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). Understandably, unpredictable cyclone events, heat-related mortality and overheating risks in buildings are alarming to investigate the vulnerability of homes to overheating in Myanmar for the resilience and thermal performance of Myanmar housing.

As the world warms up, the energy demand for space cooling accelerates, and the emissions of human-caused (anthropogenic) greenhouse gases increase. As the greenhouse gases increase, the world warms up, and the energy demand for space cooling accelerates. In order to exit this dangerous loop, the residential building sector needs urgent adaptation to cope with climate change impacts on building and construction. Therefore, building thermal performance design with a low or nearly zero energy use becomes a global interest to reduce not only the environmental impacts but also its energy-related costs. In 2010, residential buildings accounted for 24% of total global final energy use, which was three times higher than commercial buildings (IPCC, 2014b, p678). This figure shows that the residential building sector seems to be the single largest emitter of all carbon dioxide emissions in the world (Jennings et al., 2011). In the building sector, the most significant energy savings potential is in heating and cooling demand, mainly due to building envelope improvements and high efficiency and renewable equipment (IPCC, 2018, p142). Analysis of two environment chambers, which was tested in the hot climate of China, showed that the indoor thermal environment of the energy-efficient chamber was less affected by the outdoor environment and could be maintained at more comfortable conditions with less energy consumption than the basic chamber, offering a saving of up to 23.5% in air conditioning energy consumption during the summer-time test period (Fang et al., 2014). This example of research shows the effectiveness of energy-efficient building envelope for building thermal comfort; therefore, building thermal performance design with low energy use should be a national interest issue for Myanmar in addition to being a global interest, not only to reduce the environmental impacts but also to improve quality of life and lower energy-related costs.

The implementation of energy efficiency interventions in buildings improves indoor conditions resulting in significant co-benefits for public health, through (1) reduction of indoor air pollution, (2) improvement of indoor environmental conditions, and (3) alleviation of fuel poverty, particularly in cold regions (IPCC, 2014b). The alleviation of fuel poverty in the tropical regions can be considered from space cooling. In this case, understanding the statistic of material use in Myanmar housing is an important start to review. Myanmar's 2014 Census data reported that 38% of dwellings are made of timber, 34% of bamboo, and 33% have thatched roofs; all of these are considered using vernacular material in the tropics. Only 16% of dwellings are made of brick and concrete, while 62% have corrugated metal roofs (Ministry of Labour, 2015). These proportions of building material use explain the importance of vernacular architecture in Myanmar, which is predominantly dependent on natural ventilation, roof shading and passive cooling for thermal comfort. Vernacular architecture has been directly linked to locally available resources and people's skill set, embedding cultural wisdom and intimate knowledge of place in the built environment. It comprises technology or applied science that has been evolved by "trial and error" over many generations. The review of housing in Myanmar (Chapter 1) has been discussed vernacular architecture in Myanmar; assessing the effectiveness of passive cooling techniques in

Myanmar houses (Chapter 3) was then presented using simulations experiments.

While the built form and materiality of vernacular buildings may suggest their climatic provenance, in itself, this is hardly proof of all-year environmental performance (Weber and Yannas, 2014), including building thermal performance for which the social norms and occupants habitual behaviour are essential objectives to consider. For instance, as an international example, the indigenous Kaluli longhouse in the tropical rainforests of the Great Papuan Plateau is essentially used after dark, when the nocturnal temperature noticeably drops from daytime norms (Loupis, 1983). Some vernacular buildings might have constraints to provide adequate building thermal comfort. For instance, vernacular housing in Vietnam experiences 6% of the year with conditions warmer than 31°C (Nguyen et al., 2011). Moreover, post-colonialism and globalization have exerted significant cultural impacts and economic imperatives on tropical vernacular architecture (Lefaivre and Tzonis, 2001), including Myanmar. Therefore, it is urgently necessary to explore whether both vernacular houses and modern houses in Myanmar are fit for future climate conditions, and what could be improved in building thermal performance design, but there is a dearth of research for this scope of work. In this thesis, the two-years long monitoring and fieldwork investigations of the indoor thermal performance of vernacular and modern dwellings in Myanmar, which were presented in Chapters 4 and 5, attempted to fill this research gap.

Market research by the Japan Refrigeration and Air Conditioning Industry Association showed that overall air conditioning demand in Myanmar increased from 70,000 air-conditioners in 2011 to 206,000 in 2016, which is approximately a threefold increase (JRAIA, 2017). Consuming space cooling load depends on many circumstances, including the socio-economic condition of the country, decreasing household size, increasing levels of wealth and lifestyle changes and changes in the weather outdoors. Although the energy demand for space cooling in Myanmar is unknown, there is certainly a rise in short-term solutions for thermal comfort by means of air-conditioning. Cooling energy use is growing in Myanmar, where, with proper attention to useful components of vernacular design combined with modern passive design principles, mechanical air conditioning would not be needed. If building operation is switched from vernacular passive cooling to mechanical cooling, it needs to review the building thermal performance design through its envelope.

The report of the *Climate Asia* project (Colquhoun et al., 2016) stated that people interviewed in Myanmar had perceived widespread changes in the weather over the last ten years. Many feel that temperatures are on the rise, while half feel that rainfall has increased. The survey of the Climate Asia project found that people who are adapting want to take more action: 65% of people who have made changes to their livelihoods feel that more change is needed. Among this group, 70% feel willing to make further changes, compared with 31% of those who have not made changes. The report also found that awareness of the 'climate change' term is very high in Myanmar: 93% of the people from the survey said they had heard of it. However, awareness of this term did not reflect a higher understanding of it. Only 35% of people from the survey felt confident that they knew what the term meant. Many say they feel the impact of weather and environmental changes in their everyday lives, particularly on their incomes and health. At the same time, many are resigned to changes in the environment and feel powerless to make changes. Communication and specific information generated for local context can address this, highlighting how individuals can take action and the benefits of doing so. Overheating is often defined by a particular temperature above which a given proportion of people in a building vote on comfort scales; a building is considered overheating above the temperature. The thermal thresholds for building design are crucial for thermal technology (Roaf et al., 2005, p46); however, hitherto, no research and assessments have provided the thermal threshold, as well as thermal or energy performance of free-running housing for the Myanmar context.

Substantial changes in response to societal, demographic, climate change, and resource availability factors (which was discussed in Chapter 1) entail that almost everything has changed in the making of homes in the 21st century compared to vernacular homes for Myanmar people a few centuries ago. Myanmar is widely considered one of the most vulnerable countries in the world to the impacts of climate change, and its renowned biodiversity and natural resources are under increasing pressure as the country develops. Despite acknowledging the long-term climate risk index since 1990, Myanmar only formulated targeted action in the *Myanmar Sustainable Development Plan* (MSDP) in 2018 (MSDP, 2018), which includes promoting resilient housing and sustainable building design. Subsequently, the President of Myanmar HE U Win Myint announced national environment and climate change policies to mark World Environment Day (June 5) 2019 (UN-Habitat, 2019). The MSDP is the expression of Myanmar national development vision – a vision that finds resonance in the global sustainable development agenda. Its framework consists of 3 pillars, 5 goals, 28 strategies, and 251 actions plan. Its strategy 5.2 is "Increase climate change resilience, reduce exposure to disasters and shocks while protecting livelihood, and facilitate a shift to a low-carbon growth pathway". These are aligned with *United Nation Sustainable Development Goals* SDG 11 (sustainable cities and communities) and SDG 13 (climate action). The Myanmar housing strategy is stated in section 5.6.7 of MSDP as to "develop low-cost housing and housing for vulnerable groups and implement affordable housing projects including resettlement of squatters and the improvement of slum areas) (MSDP, 2018). As Climate change is a cross-cutting issue, line ministries and agencies in climate-sensitive sectors are essential to be involved. All those goals and strategies are critical; however, the research and literature of sustainable and resilient building design for the Myanmar context have hitherto been absent in Myanmar National Building Code. Furthermore, no sections were discussed the building thermal performance design for climate change in Myanmar.

The effective use of passive building design plays a key role in the context of sustainable and resilient building design. Therefore, building codes and regulations, regardless of differences in climates and countries, have promoted sustainable and high thermal performance building design approach with passive design. However, limited information for building thermal performance is found in the *Myanmar National Building Code* (MNBC). In

2016, the draft MNBC was published; four years later, the MNBC 2020 is published. Myanmar Engineering Council[3] confirms that the code shall apply for building matters with the effective date of 1 Nov 2020. In the MNBC 2020, a yardstick for Myanmar green building market is briefly introduced. In Myanmar, the Myanmar Green Building Society (MGBS) defines three grades to recognise as "green building". In terms of evaluation, the MGBS set the grades as –

- Grade A (if score > 80% for Excellent satisfaction),
- Grade B (if score between 60% to 80% for Good satisfaction), and
- Grade C (if score between 40% to 60% for satisfactory)

According to the MGBS, the rating is based on various international green building rating systems (LEED, Green Star, BREEAM, GBI, Green Mark). Furthermore, the MNBC 2020 (in the section of Green Building Rating System, p169, Part 2) stated that- "For new constructions or major retrofitted buildings, green building grading system shall be practised by Myanmar Green Building Society".

Section 2.12 of the MNBC on 'Green Building' was mainly adopted from Singapore's Code of Practices due to the lack of Myanmar context-based research. Moreover, consideration of the climate change conditions is not well-developed in the MNBC. Instead, the building energy and thermal performance standard need to be tailored for the context of Myanmar, including the consideration of recent and future climate scenarios. Furthermore, which parameters and variables should be involved and calculated for the green building design for Myanmar is not well developed yet. The empirical and quantitative assessments are essential in generating specific scientific information for sustainable climate adaptation strategies in Myanmar housing that directly rely on the research developed on the Myanmar climates and contexts. In this case, it is important to highlight that the Canadian home rating system is adapted from the United States Green Building Council's Leadership in Energy and Environmental Design (LEED), and tailored particularly for the Canadian climates, although the country is located beside the United States.

[3] http://www.myanmarengc.org

Rather than using tick boxes for the inclusion of building design elements (i.e., whether included shading, Low-E glazing and energy-efficient fixture or not), it is essential to define how the synergistic effects of design elements work for a building. Myanmar needs to develop the national code for green building based on the Myanmar context. On the other hand, Myanmar can and should learn both passive and active design approaches for building thermal performance design from other countries and other climates.

There have always been systems of proportions from building thermal envelope, mostly mathematical and sophisticated calculations between the weather outdoor and indoor thermal environment, all of which define the level of building energy and thermal performance separately. The heat storage and heat exchange in a building are not at equilibrium; therefore, buildings are not in a steady-state condition practically. Whist the heat balance method discourages natural ventilation, the adaptive method enables it (Roaf and Nicol, 2017). In the adaptive comfort method, the implications of air movement and humidity are considered, which have particularly significant impacts in hot-humid tropical contexts. The usefulness of passive design techniques in vernacular architecture, which often deploys the adaptive comfort method, lies in the way they respond to issues in the local context, rather than their product attributes; therefore, identification of general principles and mechanisms are more crucial to understand their important insights, rather than basic facts and figures (Asquith and Vellinga, 2006, p14). The thesis was further developed on how the thermal performance of Myanmar housing can be improved by introducing the Passivhaus' Fabric-First approach, which uses an energy-balance thermal envelope. If the Passivhaus principles are applied in the tropical climate context, which by definition differs from cold climate characteristics, the thermal comfort quantification for the studied climate is necessary. Therefore, the review of Passivhaus standard for tropical climate (Chapter 2) attempted to discuss this respect; the hypothesis of Passivhaus standard to Myanmar climate was then developed in this thesis (Chapters 6 and 7).

As the current climate change trends are expected to continue throughout the remainder of the 21st century and beyond, the built environment of Myanmar should be prepared for the adaptability of buildings to perform in changing climatic conditions. However, there is no empirical research that accounts for the effect of climate change on Myanmar housing. Understandably, there is a lack of empirical and quantitative assessments and qualitative assessment of occupant comfort to generate more specific scientific information for sustainable climate adaptation strategies in the MBC and housing design practices. In order to address the compounding issues, i.e., the long-term climate risk index, lack of empirical datasets and assessment of building thermal comfort, several case studies were structured in this thesis to investigate the thermal performance of Myanmar housing in a changing climate context.

It is hoped that the thesis will support future research development to empower design and construction in Myanmar to meet the needs of the nation in the challenging climate changes that lie ahead in the coming years.

Research aims, method and questions

Despite the long-term climate risk index for the period 1990-2018, Myanmar only formulated targeted actions of the Myanmar Sustainable Development Plan in 2018 and announced national environment and climate change policies in 2019. There is a dearth of research and understanding of the vulnerability of homes to overheating in Myanmar, in both academic literature and the Myanmar Building Code. Adapting buildings for climate change impact are still beyond the normal scope of what the built environment of Myanmar is prepared for. This thesis addresses concerns about climate change impacts on Myanmar housing, particularly for the thermal performance of detached houses, which comprise the main housing type in Myanmar. There are three important research gaps in the Myanmar context: (1) whether current Myanmar housing delivers adequate thermal comfort remains unknown; (2) no data sets are containing real-world indoor thermal performance parameters of Myanmar housing; (3) there is a lack of research approach and quantitative assessment of building thermal performance research for the current and future climate scenarios. In order to fill these research gaps, this thesis was structured based on the review of Myanmar vernacular architecture, introducing the Passivhaus fabric-first approach for building thermal performance design.

Using a one-year-long monitored data set and simulation experiment for a vernacular dwelling and a modern dwelling in Myanmar, this thesis adopted a “case study research method with multiple cases”. Different sources of information, therefore, can be evaluated and tested a concept on the basis that a consensus of the findings will yield more robust results (Proverbs and Gameson, 2008, p99). With an aim to improve the thermal performance and resilience of Myanmar housing in a changing climate, the method was established from multiple sources of evidence generated from three studies: (1) vernacular case studies, (2) field case studies, and (3) fabric-first variable case studies.

Four objectives set out to investigate improving building thermal performance design in Myanmar housing and address the conflicts between tropical vernacular practices and the fabric-first approach. The first objective was to investigate “the lessons learnt from Myanmar vernacular architecture”, with an aim to develop in-depth knowledge of passive vernacular design features. The second objective was to investigate “the impacts of climate change and overheating risks in Myanmar housing”, using empirical data sets. The third objective was to investigate “the impacts of the Passivhaus’ fabric-first approach on the Myanmar contexts”; particularly, the synergistic effects between shading and Passivhaus thermal building envelope properties were investigated in this thesis considering the requirements of building thermal performance and earthquake resistance designs for the Myanmar context, as discussed in Chapter 2. The fourth objective was to present “a review of barriers, challenges, and limitations of adopting the Passivhaus’ fabric-first approach in Myanmar”, considering climate, and passive approach design methodology differences between the Passivhaus and tropical climates. Vernacular case studies and field case studies addressed the first and second objectives of the research, and the fabric-first variable case studies addressed the other two objectives. The thermal performance of Myanmar housing in a changing climate was investigated in this thesis, based on the late 2000s weather data and recently monitored empirical data sets. The following questions are central to the four objectives of the research scope.

Studies	Objectives	Research Questions
Vernacular case studies	I. To review the lessons learnt from Myanmar vernacular architecture	RQ1. How do the vernacular practices in Myanmar housing provide thermal comfort, and does the building thermal performance of Myanmar vernacular housing cope with climate change?
		RQ2. To what extent can the resilience of vernacular passive design techniques used in Myanmar housing improve the indoor thermal environment for future climate scenarios?
Field case studies	II. To investigate the impacts of climate change and overheating risks in Myanmar housing	RQ3. What are the differences between the typical weather year and recent weather year, and how those changes in climates impact the thermal performance of Myanmar housing?
		RQ4. How do the vernacular and modern dwellings in Myanmar thermally perform in the present weather year compared to a typical weather year?
		RQ5. How does the building thermal performance vary in terms of the building envelope design, i.e., in vernacular and modern buildings?
		RQ6. How do different local climates affect the building thermal performance design in future climate scenarios?
Fabric-first variable case studies	III. To investigate the impacts of the Passivhaus' fabric-first approach on the Myanmar contexts.	RQ7. Which Passivhaus parameters are more sensitive in tropical climates compared to cold climates?
		RQ8. How do the synergistic effects between shading and the Passivhaus thermal building envelope influence the tropical Passivhaus building design?
		RQ9. How do the synergistic effects between the cool roof and Passivhaus thermal building envelope influence the tropical Passivhaus building design?
	IV. To present barriers, challenges, and limitations of adopting the Passivhaus’ fabric-first approach in Myanmar	RQ10. How does the Passivhaus building envelope differ compared to the vernacular construction in Myanmar?
		RQ11. How does the Passivhaus’ fabric-first building envelope approach perform differently according to the climate differences in Myanmar?
		RQ12. What are the challenges of adopting the Passivhaus' fabric-first approach in Myanmar in terms of its original context, climate, and methodology differences?

Hypothesis of Passivhaus Standard to Myanmar Climate

The Passivhaus' fabric-first approach was introduced in this thesis to develop design strategies improving the building thermal performance of Myanmar housing. Passivhaus is a building design and delivery concept created by the Passive House Institute[4] (PHI) in Germany that suggests a set of design criteria developed to limit operational energy used whilst achieving maximum thermal comfort (Feist et al., 2019, iPHA, 2016, Passivhaus Trust, 2020). Passivhaus buildings are known for the provision of a high level of occupant comfort while using very little energy for heating and cooling, and can be certified through an exacting quality assurance process (Gonzalo and Valentin, 2014). The Passivhaus standard uses the heat balance method for steady-state calculations (Feist et al., 2019). If the Passivhaus principles are applied in the tropical climate context, which by definition differs from cold climate characteristics, many questions arise concerning the tropical climate elements and building thermal envelope design, particularly if a house uses an adaptive thermal comfort model. Therefore, the hypothesis below was proposed in this thesis.

The thesis aimed to fill the research gaps and develop the methods to meet the objectives of this thesis presented in the previous section. In order to develop the Passivhaus concept in the tropical climate, the fabric-first variable case studies of this thesis governed evidence in support of the following hypothesis.

> **"There is potential and possibilities to improve the thermal envelopes of Myanmar housing in the tropical climates by the use of optimum variables from the fabric-first approach originated from the PassivHaus standard".**

Independent assumption and research methodologies of the fabric-first variable case studies were presented in Chapters 6 and 7.

[4] The Passive House Institute (PHI) is an independent research institute that has played an especially crucial role in the development of the Passive House. It was founded in 1996 by Dr. Wolfgang Feist. The Passivhaus standard originated from a conversation in May 1988 between a Swedish scientist Bo Adamson of Lund University and German physicist Wolfgang Feist of the Institute for Housing and the Environment, Darmstadt.

Thesis outline

The diverse nature of the case studies required to comprehensively answer the research question set out below; therefore, all the chapters were self-contained with respect to having independent backgrounds, methodologies, results, analysis, and conclusion. A summary outline of the thesis is presented in Table 0-1 and below.

Chapter 1 introduces the "*Housing in Myanmar"* and particularly focuses on the passive building design techniques in Myanmar architecture for thermal comfort. This chapter presents the review of how Myanmar's vernacular architecture has undergone significant customisation such as changes in building forms, building plans, building materials and decorative features to meet a wide range of complex needs and social-economic limitation, based on geographical contexts and climate change risk.

Chapter 2 presents a review of *"Thermal comfort and building thermal performance"* and particularly focuses on the tropical Myanmar climate contexts. This chapter firstly presents the review of thermal comfort in world vernacular architecture which linked to Myanmar vernacular architecture. Secondly, in order to address the conflict between Myanmar vernacular architecture and Passivhaus' fabric-first approach, the thermal comfort quantification of the adaptive thermal models for the Myanmar climate contexts were reviewed. Then, the chapter presents the review of the Passivhaus' fabric-first standard and discusses its adaptability, barriers and challenges in the Myanmar context.

Chapter 3 presents a case study of *"Assessing the Effectiveness of Passive Cooling Techniques through Simulations";* there were two simulation case studies: an investigation into passive design techniques used in Myanmar vernacular houses based on the data obtained from the field visit, and a thorough review of multistage roof typologies followed by an investigation of their thermal performance in various prescribed scenarios.

Chapters 4 and **5** present two case studies of *"Assessing Overheating Risk in Vernacular and Modern Dwellings through Empirical and Simulation Studies.*

That was a fieldwork that investigated the indoor thermal performance of one vernacular dwelling and one modern dwelling in Myanmar using a one-year monitored data set. The validation between the indoor thermal environment data of the monitored dwelling and simulation models was presented in both chapters that provided the empirical data sets for further study in Chapter 7.

Chapter 6 presents a case study of *“Assessing the Effectiveness of Shading and Roof Materials and Passivhaus Parameters”;* there were two simulation case studies. For the Passivhaus concept to be effective in tropical countries and future climate change scenarios, in the review of the Passivhaus standard (Chapter 2), there is a need for a detailed investigation of the contribution of passive strategies such as shading to the overall balance, and of the possibilities of relaxing the building envelope parameters to suit local contexts. Therefore, the first study hypothesised that slightly higher U-values for wall and floor could be more effective in the climate of Myanmar than the U-values suggested by the Passivhaus standard and tested the hypothesis with various prescribed shading scenarios. The second study investigated the impacts of the thermophysical properties of external building envelopes on the present typical weather and predicted climate scenarios in Myanmar.

Chapter 7 presents *“Investigating the Passivhaus' Fabric-first Parameters in Studied Dwellings”*. That was an extension of the field studies, where the building envelopes of the dwellings were switched to Passivhaus parameters using simulation experiments. It addressed the challenges of Passivhaus' parameters in the Myanmar climate contexts based on the empirical data sets obtained from Chapter 4 and 5. The central issue of concerns in this chapter was to investigate whether the Passivhaus concept is adaptable in the tropical climates in terms of their methodology difference between the Passivhaus’ fabric-first approach building envelope and tropical vernacular construction practices.

Chapter 8 is the concluding chapter that deals with a discussion of the findings presented in all case studies. It answered the research questions and addressed the issues, potential and possibilities to improve the tropical building thermal envelope in Myanmar.

Table 0-1. Flow chart of research presented in this thesis

Chapter	Description	Case Studies	Research Questions	Outputs Publications
-	Introduction	-	-	
1	Housing in Myanmar	Literature review	-	(Zune et al., 2020a, 2020c, 2020d)
2	Thermal comfort and building thermal performance	Literature review	-	Potential publications
3	Passive cooling techniques study through simulation	Vernacular case studies	1 - 3	(Zune et al., 2019a, Zune et al., 2018a, 2019b, 2020d)
4	Vernacular dwelling study	Field case studies	2 - 6	(Zune et al., 2020b)
5	Modern dwelling study	Field case studies	2 - 6	(Zune et al., 2020e)
6	Solar shading and roof material study in simplified models	Fabric-first variable case studies	7 - 9	(Zune et al., 2018b)
7	Passivhaus' building envelope material properties study in two dwellings	Fabric-first variable case studies	10 - 12	Potential publications
8	Conclusion and future works	-	-	-

Contribution to research

The work presented in this thesis has resulted in reputable building journals and several conference papers. This thesis contributes to new knowledge and empirical evidence, including the following:

- A novel review of passive design techniques used in Myanmar vernacular houses and traditional buildings with multistage roofs, to achieve thermal comfort based on the present climate and future climate scenarios (Zune et al., 2020a, 2020c, 2020d).
- Understanding of how the use of vernacular materials, layout, and building form can provide thermal comfort in Myanmar housing, while

identifying challenges concerning current and future climate scenarios (Zune et al., 2019a, Zune et al., 2018a, 2019b).

- Providing a record of one-year empirical data set for two cities to enhance the reliability of findings from the simulation case studies (Zune et al., 2020b, 2020e).
- Contributing valuable insights such as an understanding of the vulnerability of homes to overheating in Myanmar, particularly from the impact of climatic elements on thermal comfort, the impacts of changes in monsoon onset and withdrawal time, warmer night temperatures, and the urban heat island effect on the indoor thermal environment, and the impacts of different building envelope material properties (Zune et al., 2020b, 2020e).
- Contributing new knowledge and evolution of how the Passivhaus building envelope shows a high level of building thermal performance compared to a typical lightweight, not-insulated building envelope in the Myanmar climates.
- Understanding of how the building thermal performance of Myanmar buildings can be strengthened and how the earthquake resistance design approach can be integrated by adopting the Passivhaus standard with extensive shading and cool roof, and how the Passivhaus approach can bring both passive technology solutions through building fabric and potential hybrid ventilation (Zune et al., 2018b).
- Contributing new knowledge for adopting the Passivhaus fabric-first approach in the tropical climate context, to improve the building thermal performance to cope with climate change impacts on buildings.
- Establishing tailored information to unify the Myanmar building code and potential influence on future policy relating to building thermal performance design in Myanmar that will support mainstream climate change into the Myanmar housing policy development.

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“Debating Burma”

ELAINE: "Peterman ran off to Burma"

SEINFELD: "Isn't it Myanmar now?"

KRAMER: "Myanmar...

isn't that discount pharmacy?"

~ Thant Myint-U,

from The River of Lost Footsteps, p31.

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1. Housing in Myanmar

Myanmar is located at a strategic location for a trade hub near the major Indian Ocean shipping lanes. The country is sandwiched between two of the biggest civilizations in Asia – India in the northwest and China in the northeast. Many scholars believe that the first-known human settlement in Myanmar was from the Tibeto-Burman-speaking people and the Mon or Talaings (Harvey, 1925, Myint-U, 2008). From AD 700 to 1824, the Mon, Bamar, Rakhine, and Shan have been the foremost traditional ethnic groups of Myanmar, with dispersed ethnic groups spread throughout the country (Harvey, 1925). It was called Burma throughout most of history, as an intermediary in the Indian Ocean maritime civilization, between the world of Islam in the west and China in the east, and later as an ancillary consideration of European imperialism in India and China (Myint-U, 2008, p42). Today Myanmar is the product of three historical epochs in the nation's history: British Burma (1824–1948), the socialist period (1948–1988), and the military junta period (1988-2011).

Regional climates and topography have had a tangible impact on human settlement and house design (Taylor, 1982). Ancient Myanmar village settlement patterns are found along the Irrawaddy rivers as a linear village type, or over the countryside as a nucleated village type (Taylor, 1982), predicated on agricultural economics, fishing, and domestic animal husbandry. Much of Myanmar's art and architecture is tied to ancient Hindu-Buddhist culture that can be traced to the country's earliest known inhabitants. Historically Myanmar has been a land of eclectic political, cultural, and religious beliefs (Jesse, 1946, p112), and it is essential to appreciate the country's rich diversity to grasp its essence. Numerous ethnicities and cultures are found in Myanmar, of which eight groupings are numerically significant, based on their population distribution (CIA, 2017, Laoi, 2014), and each has particular housing typologies. This chapter covers the review of eight houses for major ethnic groups in Myanmar.

Understanding the context of the residential building sector in Myanmar and how it responds to historical and typical climate contexts is fundamentally important to improving building thermal performance. This chapter introduces passive building design techniques used in Myanmar from two areas: Myanmar vernacular architecture and modern customs in Myanmar buildings during the 19th – 21st centuries. This chapter covers relevant case study cities and their climate contexts as a precursor to the analysis presented in the following chapters.

1.1 The context of Myanmar

The land of Myanmar is bordered by the Andaman Sea, the Bay of Bengal, Bangladesh, India, Tibet, China, Laos, and Thailand. The country is 432.41 km wide, 1009 km long, and approximately 702 meters above sea level. Myanmar lies between the latitudes 9° to 29°N and longitudes 92° to 102°E; the latitude differences, highlands, and topography create slightly different climate zones throughout the country. Only 3.4% of the total area of the country is covered by water (CIA, 2017). On the western side is a long coastline, while the country itself extends through 18 degrees of latitude; as a result, Myanmar's climate ranges from the subtropical highland climate at the snow-covered mountain peaks in the north to tropical monsoon climate in the south. Between these extremes of highland and tropical climates is a dry zone, corresponding to a range between the equatorial winter dry climate and mixed humid subtropical climate (Rubel and Kottek, 2010). According to the Köppen-Geiger climate classification (Kottek et al., 2006, Rubel and Kottek, 2010), as of 1976-2000, there are different distinct climate zones in Myanmar: subtropical highland climate (Cwb), mixed humid subtropical climate (Cwa), equatorial winter dry climate (Aw), and tropical monsoon climate (Am) (Figure 1-1). The climate Cwa only covers very small areas in the north of Myanmar; therefore, three distinct climate zones are found in Myanmar.

Due to the global arrangement of prevailing surface winds, two major wind currents run throughout the year in Myanmar. Over the Indian Ocean and the south-west Pacific, the direction of the global southeast trade wind is reversed by the southwest monsoon wind due to the landmass of Myanmar. Strong winds come from a southwest direction in June, and cold winds come from a northeast direction in January (Aung et al., 2017). As a result, Myanmar experiences three distinct seasons – the hot, wet, and cool seasons – they are annually changed by global prevailing winds, the monsoon onset and withdrawal times, due to its location around the Tropic of Cancer. In addition to the diversities in culture and ethnicities, regional climates and seasonal variations have significant impacts on housing design. Therefore, it is important to review the effect of different Myanmar climate contexts on housing design.

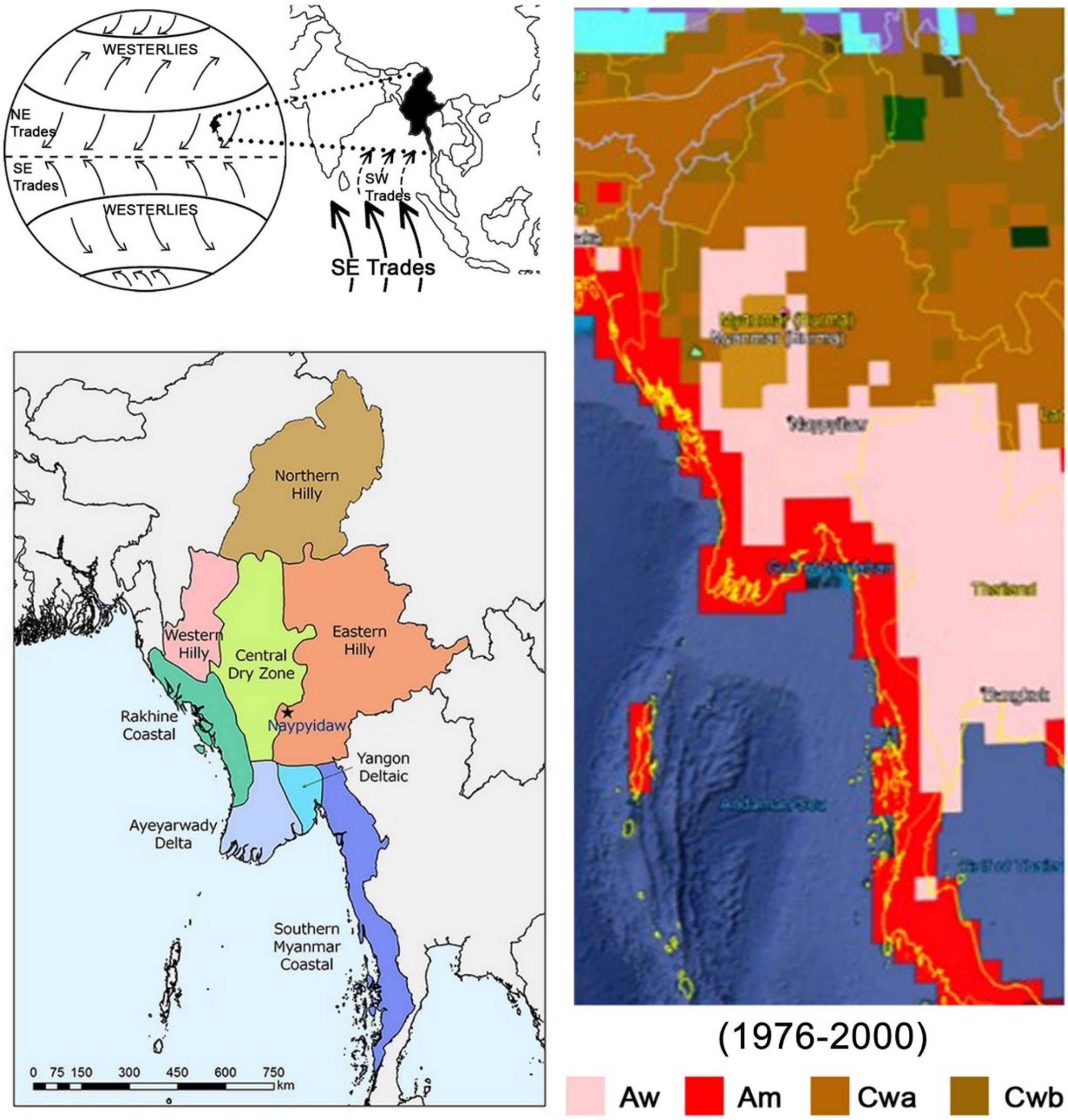

Figure 1-1. Myanmar geography map (Horton et al., 2017)and Köppen climates in Myanmar (Zune, 2017d)

1.1.1 Climate change risk

Myanmar has been ranked second out of 183 countries in the long-term climate risk index for the period 1990-2018 (Eckstein et al., 2019, Harmeling et al., 2011), and it continues to be at high risk. It is fundamentally important to understand how Myanmar is placed at risk by climate change. The risk triangle developed by Crichton (2001) is a good reference to analyse the extent of climate change risk in Myanmar from three components: exposure, hazard, and vulnerability.

Exposure: Exposure to climate change has been defined by the Intergovernmental Panel on Climate Change (IPCC) as “the nature and degree to which a system is exposed to significant climate variations” (IPCC, 2014d). The degree to which any population will be exposed to different scenarios of climate models is related to what has been driven for the climate change for one country, regionally and globally. Population growth is also considered one of the underlying contributors to global warming. In 1872, the population of Myanmar was estimated to be 2.7 million inhabitants; by 2014, this number had increased by 19 times to 51.5 million (Ministry of Labour, 2015). In 1990, 56% of the total land area was covered by forest; however, it is projected that only 25% of the total land area will be covered by forest in 2060 (Myint, 2016). Lost forest areas in Myanmar are mainly in the highlands of the north, east, and west of the country, which are more exposed to significant climate variations than other areas. Deforestation, which is usually associated with increased flooding and decreased soil quality, is one of the main contributors to climate change and its impacts in Myanmar.

The IPCC[5] report, as shown in Figure 1-2 for a global scale, showed a change in average surface temperature and precipitation based on multi-model mean projections for 2081-2100 relative to 1986-2005 under different Representative Concentration Pathways (RCP) scenarios; for instance, the increase of global mean surface temperature by the end of the 21st century is predicted to be 2.6°C to 4.8°C under RCP 8.59[6] (IPCC, 2014c, p12). According to the report “*Assessing the Climate Risks in Myanmar*”, as shown in Figure 1-3 for the country scale, national annual average temperatures in 2011-2040 are projected to rise by 0.7 to 1.1°C compared to the 1980-2005 base period, while

[5] The increase of global mean surface temperature by the end of the 21st century (2081–2100) relative to 1986–2005 is likely to be 0.3°C to 1.7°C under RCP2.6, 1.1°C to 2.6°C under RCP4.5, 1.4°C to 3.1°C under RCP6.0, and 2.6°C to 4.8°C under RCP8.59.

[6] The worst case scenario, very high future concentrations of greenhouse gases.

warming trends may accelerate beyond 2040, raising average temperatures by 1.3 to 2.7°C[7], depending on the scenario (Horton et al., 2017). According to records covering the period 1955-2015, late monsoon onset time and early monsoon withdrawal time (Aung et al., 2017) indicate a slow-changing climate condition over sixty years in Myanmar. On the other hand, rainfall is projected to increase by 27% in the wet season compared with the 1980-2005 base period, although it is projected to decrease in the hot and cold seasons[8] (Horton et al., 2017).

The climate shift depicted by Köppen-Geiger climate classification maps[9] (Rubel and Kottek, 2010), as shown in Figure 1-4[10] for Myanmar, shows that the tropical monsoon climate and the equatorial winter dry climate are moving to the northern and eastern parts of Myanmar. As a result, the mixed humid subtropical climate and the subtropical highland climate would disappear in the northern parts of Myanmar by 2076-2100. The results in the climate shift have shown that some areas in Myanmar will experience far faster and more extreme change than other areas. For a typical climate condition, the temperature that people find comfortable is closely related to the mean temperature measured (Nicol et al., 2005, p114), and different climate contexts have a unique setting for the average and extreme temperatures. For a free-running building, the degree of exposure to adapt according to the weather outdoors can be significantly dependent on diurnal and seasonal variations; however, no research has been done for the thermal comfort study of Myanmar housing. Understandably, different degrees of exposure to extreme climate changes test the adaptability of Myanmar housing to perform in changing

[7] During the last Ice Age, only 10,000 years ago, temperatures were slightly more than 3°C colder than today.

[8] Data source for temperature projections is NASA Earth Exchange Global Daily Downscaled Projections.

[9] World Map of Köppen-Geiger climate classification calculated from observed temperature and precipitation data for the period 1901-1925 on a regular 0.5 degree (30 arc minutes) latitude/longitude grid. World maps for the period 2003-2100 are based on ensemble projections of global climate models provided by the Tyndall Centre for Climate Change Research. The main results comprise an estimation of the shifts of climate zones within the 21st century by considering different IPCC scenarios.

[10] The figure was created by using the Google Earth KMZ files provided by Koppen-Geiger web sources: http://koeppen-geiger.vu-wien.ac.at/shifts.htm.

climate conditions. Hence, it is critical to understand how significant these changes are likely to be, if the conditions of historical, present, and future climate scenarios are compared.

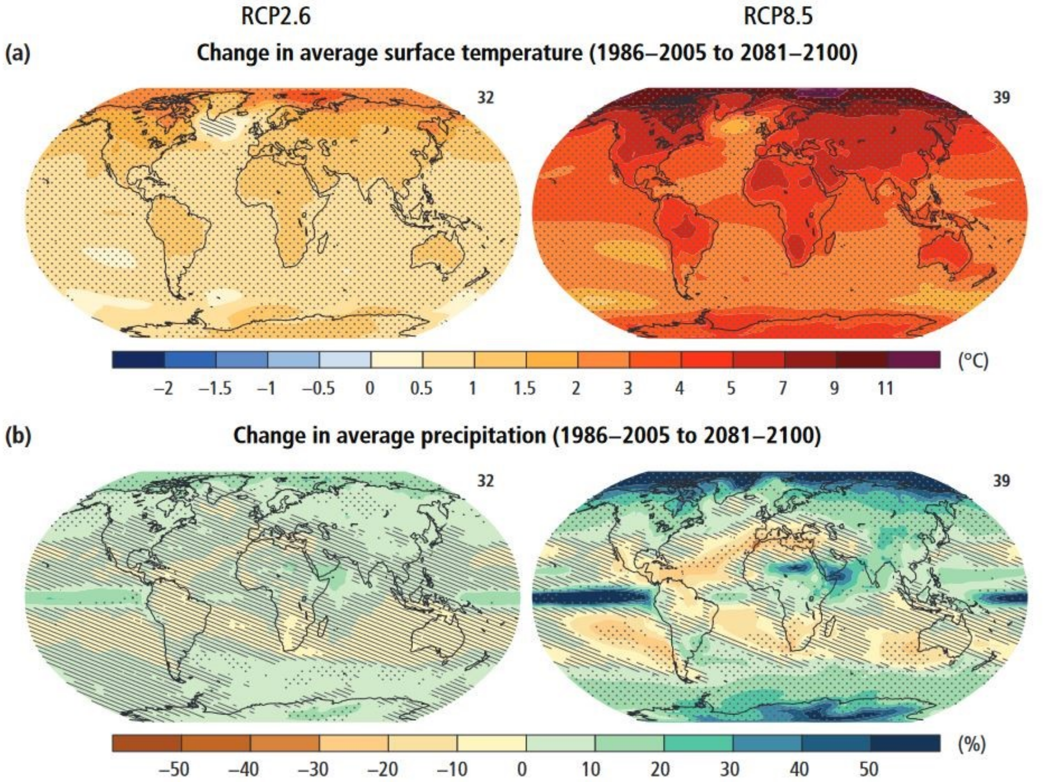

Figure 1-2. (a) Change in average surface temperature and (b) change in average precipitation based on multi-model mean projections for 2081–2100 relative to 1986–2005 under the RCP2.6 (left) and RCP8.5 (right) scenarios (IPCC, 2014c)

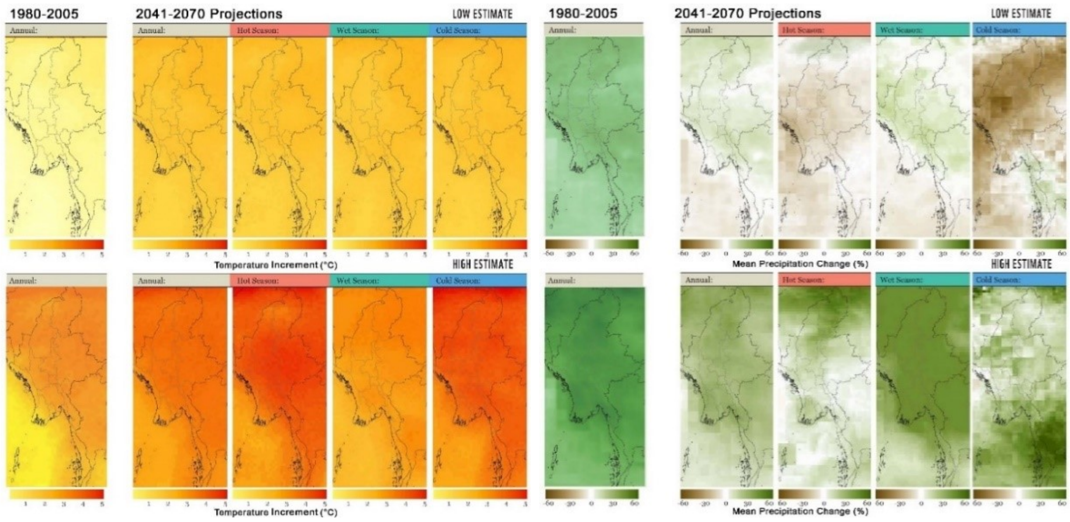

Figure 1-3. Average annual and seasonal temperature changes and rainfall changes in mid-century relative to the 1980-2005 base period under low emissions and high emissions scenarios for 2011-2040 and 2041-2070 for Myanmar in a map (Horton et al., 2017)

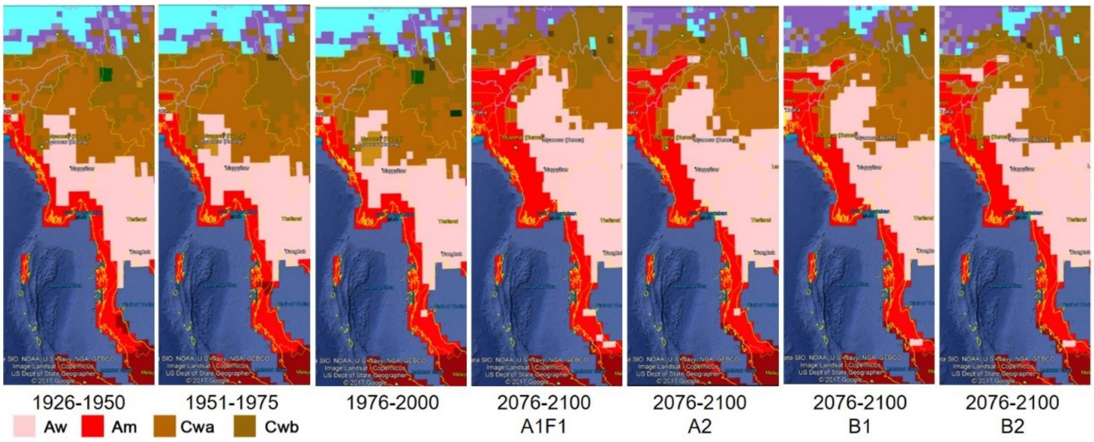

Figure 1-4. Köppen climate shift in Myanmar from 1926 to 2100 (Zune, 2017d)

Table 1-1. Average annual and seasonal temperature changes and rainfall changes in mid-century relative to the 1980-2005 base period under low emissions and high emissions scenarios for 2011-2040 and 2041-2070 for Myanmar in tabular data (Horton et al., 2017), based on the NEX-GDDP[11] dataset (NASA, 2015)

	Model baseline* (1980 to 2006)	Warming by 2011-2040	Warming by 2041-2070
Annual	23.6 °C	0.7-1.1°C	1.3-2.7°C
Hot Season	25.1°C	0.8-1.2°C	1.4-2.9°C
Wet Season	25.1°C	0.6-1.1°C	1.1-2.4°C
Cool Season	20.5°C	0.7-1.2°C	1.3-2.8°C

	Model baseline* (1980 to 2006)	Precipitation range 2011-2040	Precipitation range 2041-2070
Annual	2000 mm	+1% to +11%	+6% to +23%
Hot Season	300 mm	-11% to +12%	-7% to +19%
Wet Season	1700 mm	+2% to +12%	+6% to +27%
Cool Season	100 mm	-23% to +11%	-12% to +11%

Hazard: Hazard to climate change has been defined by the IPCC as "the potential occurrence of a natural (natural variability) or human-induced physical event (anthropogenic climate change) that may cause loss of life, injury, other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources" (IPCC, 2014c). The first one is related to El Nino[12] years in Myanmar, which is

[11] The NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) dataset is comprised of downscaled climate scenarios for the globe that are derived from the General Circulation Model (GCM) runs conducted under the Coupled Model Intercomparison Project Phase 5 (CMIP5) and across two of the four greenhouse gas emissions scenarios known as Representative Concentration Pathways (RCPs). The CMIP5 GCM runs were developed in support of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5). The NEX-GDDP dataset includes downscaled projections for RCP 4.5 and RCP 8.5 from the 21 models and scenarios for which daily scenarios were produced and distributed under CMIP5. Each of the climate projections includes daily maximum temperature, minimum temperature, and precipitation for the periods from 1950 through 2100. The spatial resolution of the dataset is 0.25 degrees (~25 km x 25 km).

[12] El Niño–Southern Oscillation (ENSO) is an irregularly periodic variation in winds and sea surface temperatures over the tropical eastern Pacific Ocean, affecting the climate of much of

linked to a short-term period of warm ocean surface temperature in the tropical Pacific, and likely cause long durations of high maximum temperatures. Higher temperatures and heatwave events were recorded in Myanmar for those years (Aung et al., 2017). Myanmar regularly experiences cyclones, storm surges, floods, landslides, earthquakes (due to the Sagaing Fault[13], Figure 1-5), droughts, and forest fires. Over the last ten years, Myanmar has been affected by two major earthquakes, three severe cyclones, numerous floods, and other smaller-scale hazards. Cyclone Nargis in May 2008 affected 2.4 million people in Myanmar as climate refugees and killed 140,000 people (OCHA, 2016). Although the natures of hazards such as cyclones and earthquakes are unpredictable, the extremity and frequency of climates undergoing change must be considered for future climate scenarios, which are also important in designing the thermal performance of buildings for changing climate conditions together with other design requirements. For instance, the own weight of a building can be increased by adding insulation or thermal mass for building thermal performance. That is also a challenge in both earthquake-related structural design and construction cost; therefore, alternative insulations are favourable to consider achieving the same performance to offset the heat transfer and protect the heat gain.

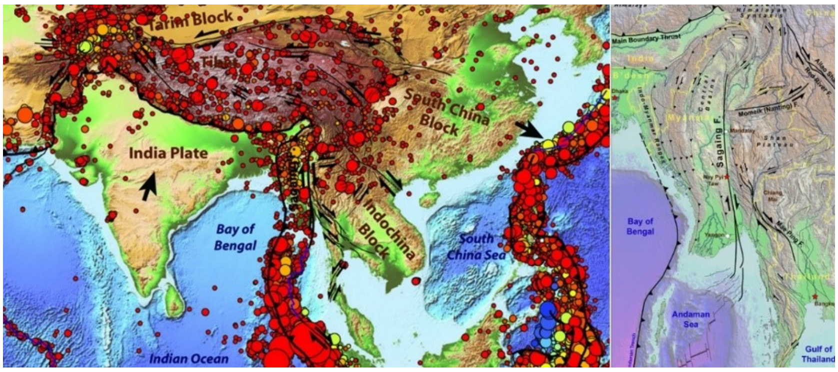

Figure 1-5 Earthquake locations from 2003 to 2013 and tectonic features of Myanmar and surrounding areas (Sagaingfault, n.d)

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the tropics and subtropics. In 2015-2016, the El Niño phenomenon was the strongest iteration since 1950, with a significant influence on weather patterns. This resulted in drought conditions with intermittent 'very severe' category cyclones in different parts of Asia and the Pacific.

[13] The Sagaing Fault is a major tectonic structure in Myanmar that cuts through the centre of Myanmar, broadly dividing the country into a western half moving north with the Indian plate, and an eastern half attached to the Eurasian plate.

Vulnerability: Vulnerability to climate change has been defined by the IPCC as “the propensity or predisposition to be adversely affected” (IPCC, 2014c). The degree of vulnerability is related to one’s adaptability to cope with the changes. For instance, occupants in naturally ventilated buildings are tolerant of a significantly wider range of temperature changes, explained by a combination of both behavioural adjustment and psychological adaptation (deDear and Brager, 1998). The thermal threshold of Myanmar subjects and occupants of naturally ventilated buildings in Myanmar is unknown. However, what can be learned from the other studies is that 90% of Japanese subjects are comfortable in their own homes with a temperature range between 18 and 28°C in their everyday lives (Nicol and Roaf, 2017), and Pakistani office workers are comfortable in a range of 21–30°C (Nicol et al., 1999). In general, humans are vulnerable outside the comfortable range of indoor temperatures (below 10°C or above 35°C). As the human temperature regime is not a simple consequence of thermal needs but rather a product of social and economic conditions (Levins and Lewontin, 1985, Roaf et al., 2005, p110), the neutral and survival temperature thresholds for one place can be varied by cultural mechanisms, but the values of these thresholds are unknown for Myanmar. However, short-term peaks in mortality are associated with heatwaves (Nicol et al., 2005). 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).

On the global scale, the number of cold days and nights has decreased, and the number of warm days and nights has increased, based on observations between 1951 and 2010 (IPCC, 2014c). Furthermore, global warming also shifts the timing of seasons, with earlier springs, shorter winters, and fewer freezing days affecting the timing of many life cycle events, ecosystems, and building design. According to the report “*Assessing the Climate Risks in Myanmar*”, as shown in Table 1-1, drier hot and cool seasons but more rainfall in the wet season are predicted in 2041-2070 (Horton et al., 2017). However, there has been little study of how design features used in Myanmar housing can increase or decrease vulnerability to climate changes. Recent severe weather events and predicted future events are causing a shift in thinking that will result in more buildings having the capability of assisting human survival in the wake of natural or human-induced disasters. Indeed, there is an urgent need to address the emerging issue of 'passive survivability', which is a term used to describe how a building should be designed and built to assist in the survival of human occupants in the wake of unpredictable climate change events.

1.1.2 Case study cities

In this thesis, it was initially set up to compare typical, recent, and present climate data from three Myanmar cities representing the three distinct Koppen climate zones in Myanmar, as shown in Figure 1-6 - the image of Manaw festival represents Myitkyina; the image of the royal palace represents Mandalay; the Shwedagon Pagoda represents Yangon. The three cities are Mandalay (21.975°N 96.083°E), Myitkyina (25.383°N 97.4°E), and Yangon (16.85°N 96.183°E).

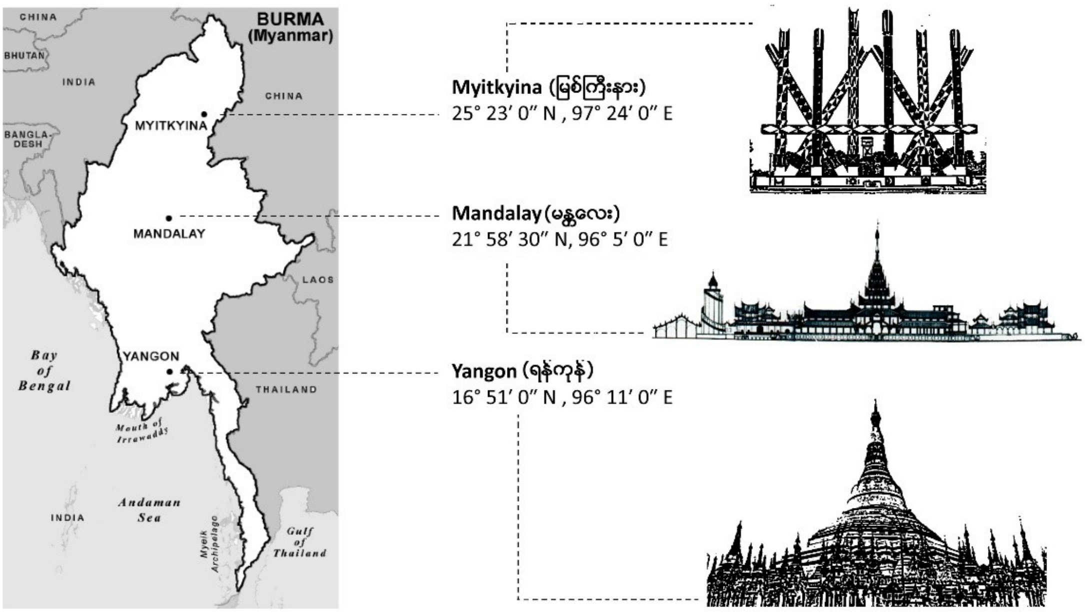

Figure 1-6. Case study cities (Myitkyina, Mandalay and Yangon) on Myanmar map (Zune, 2017c)

The typical weather files[14] used in this thesis had 22 years' worth of data, spanning from 1991 to 2013, which were generated by Huang et al. (2014) for ASHRAE. Monthly dry-bulb temperature, relative humidity and solar radiation in a typical weather year in three cities are compared in Figure 1-7 and Figure 1-8, showing salient differences between the three cities. Those typical weather data were also used in the simulation studies presented in the following chapters. Further psychrometric study for each city is discussed below. The typical weather files did not contain extremes and overheating values; therefore, average values were presented in the figures.

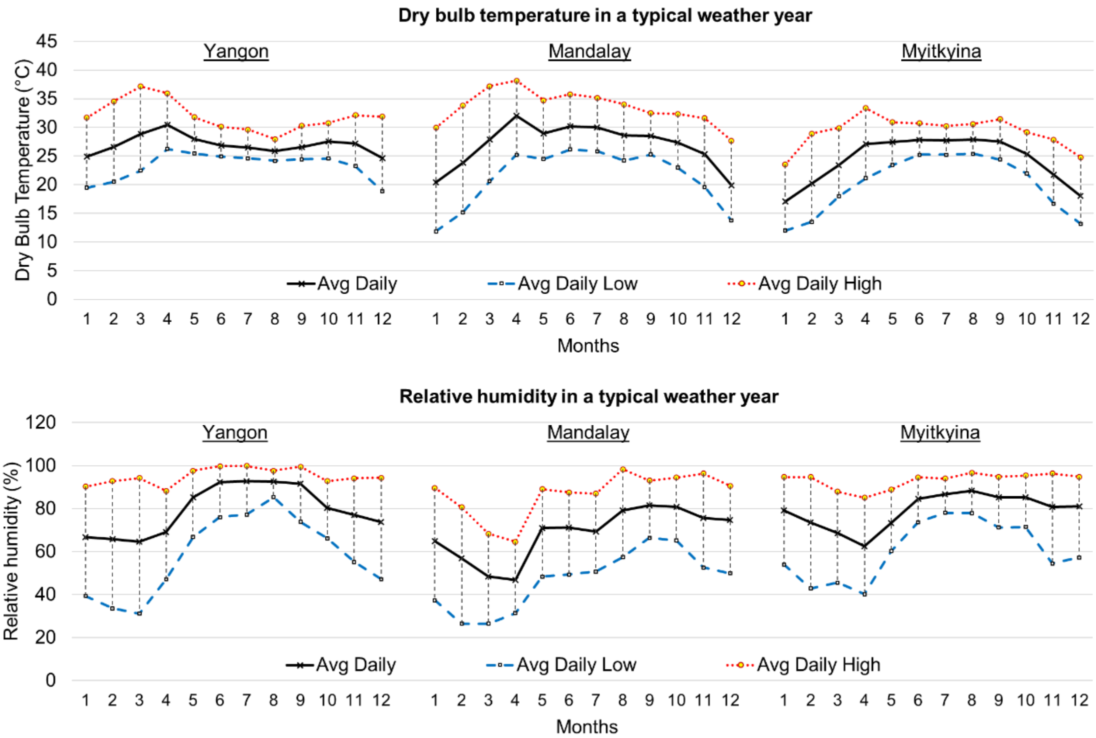

Figure 1-7. Monthly dry-bulb temperature and relative humidity in a typical weather year for three cities

[14] The typical weather file for Myitkyina was generated based on typical monthly data from different years: Jan 2011, Feb 2010, Mar 2009, Apr 2003, May 2003, Jun 2003, Jul 2003, Aug 2009, Sep 2006, Oct 2013, Nov 2005, Dec 2003.

The typical weather file for Mandalay was generated based on typical monthly data from different years: Jan 2013, Feb 2009, Mar 2006, Apr 2005, Jun 2005, Jul 2005, Aug 2007, Sept 2011, Oct 2012, Nov 2009, Dec 2007.

The typical weather file for Yangon was generated based on typical monthly data from different years: Jan 2002, Feb 2001, Mar 2002, Apr 1991, May 2006, Jun 2002, Jul 2005, Aug 1991, Sep 2003, Oct 2004, Nov 2008, Dec 2006.

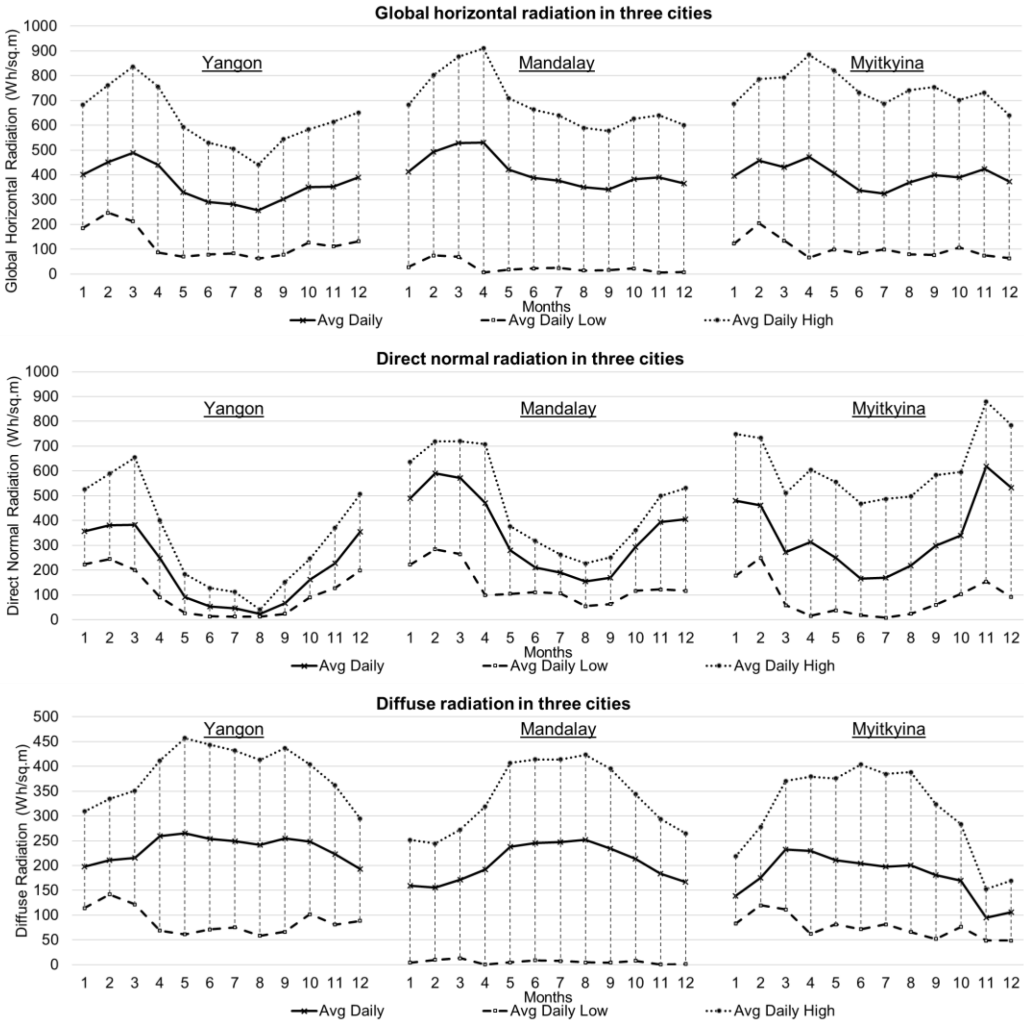

Figure 1-8. Monthly radiations in a typical weather year for three cites

Myitkyina: Myitkyina is a northern highland city in Myanmar, where the great Irrawaddy river starts forming from the confluence of the Mekha and Malika rivers. Located at an outlying subrange of the Greater Himalayan mountain range, northern Myanmar featured a warm temperate climate with dry and warm summers during the period 1926-1950 [Figure 1-4]. The sky is clear in the hot season, but the wet (rainy) season is sweltering, muggy, and mostly cloudy. Myitkyina has a long cold season than Mandalay and Yangon, and experiences extreme seasonal variation in the perceived humidity. The climate shift depicted by Köppen-Geiger climate classification predicts that the historical Köppen climate Cwa of northern Myanmar is likely to be replaced by an equatorial winter dry climate (Köppen climate Aw) in 2076-2100, due to the global trends in observed climate and projected climate change scenarios (Rubel and Kottek, 2010). Myitkyina is a city under the risks of deforestation

(Myint, 2016) and the controversial Myitsone dam[15] (Beech, 2011). From 1981 to 2010, Myitkyina's maximum temperature days greater than 38.0°C totalled 17 days in April, 38 days in May, 12 days in June, and 2 days in August (Aung et al., 2017). In the typical weather year (2003 to 2013), the annual average temperature of Myitkyina is 24.3°C, with an average daily high in the hottest month (April) of 38.1°C, and the annual average relative humidity of 60%. Chapter 4 presents the field case study of a vernacular dwelling in Myitkyina.

A psychrometric chart was used to express thermal comfort, design strategies, and energy requirements for strategies tailored to specific climates. Figure 1-9 shows the findings from using a psychrometric chart to analyse a typical weather year of Myitkyina. The vertical axis of the chart shows the hourly percentage of a year in which comfort can be achieved by using selected design strategies. It was found that comfort is achieved for less than 10% of the time in a year if no passive design strategies are adopted. If passive design strategies were considered, a time within thermal comfort could increase up to 42% by adding natural ventilation for adaptive thermal comfort, and up to 22% by adding sun shading to windows. Unlike Yangon, Myitkyina has a noticeable length of cold season with a larger diurnal temperature swing at that time, passive solar direct gain with high thermal mass is one of the passive design solutions.

Although the percentage of a year for thermal comfort could increase by adding the use of high thermal mass coupled with night flushed ventilation and passive solar direct gain, the effectiveness of thermal mass on the indoor thermal comfort had less benefit (less than 10%), compared to the use of shading and natural ventilation for passive cooling in Myitkyina, due to a long time for the hot season and rainy season. When the active design strategies were considered, the use of fan-forced ventilation alone was not as significant as the use of dehumidification. By combining active cooling with dehumidification,

[15] The Irrawaddy River is the lifeblood of Myanmar. A few years ago when Myanmar's ruling junta agreed to a $3.6 billion, Chinese-backed dam that would flood a vast area near the Irrawaddy's sacred source, few were surprised—even if many Burmese privately grumbled over a deal that would displace 15,000 people and put a potentially dangerous dam in a geologically unstable area.

indoor thermal comfort could be maintained for more than 40% of the year in Myitkyina. The psychrometric charts show the unique climate attributes and their impacts on thermal comfort, particularly the use of natural ventilation, shading, and passive solar direct gain with high thermal mass for Myitkyina.

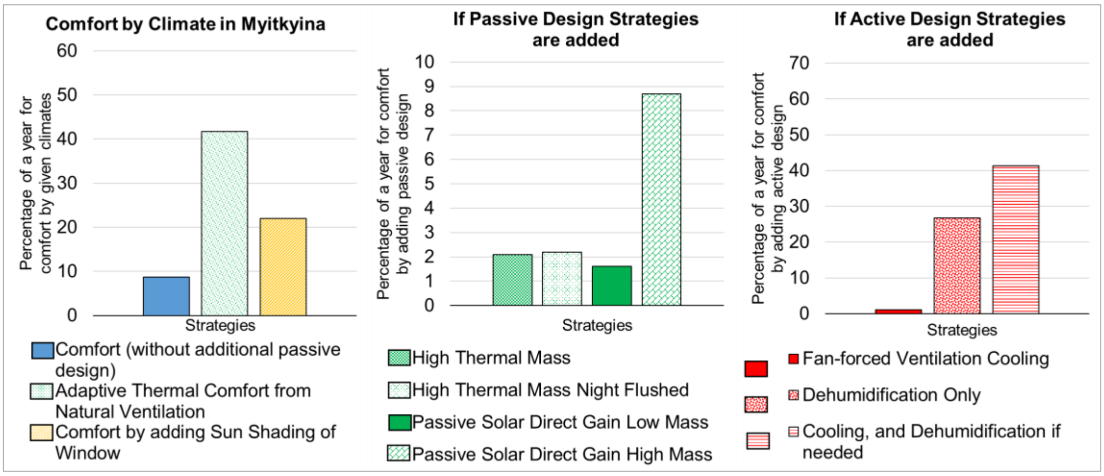

Figure 1-9. Comparison of the results of the psychrometric chart for Myitkyina

Mandalay: Mandalay, located centrally in the country, was founded in 1857 as the last royal capital of Myanmar, and it is the country's second-largest city. Bordering the Arakan Mountains, Mandalay is well known for its number of moderate to severe hot days, although the city does not have a direct hot semi-arid climate. Mandalay features a noticeably warm summer and an equal length of wet and dry seasons. According to the Köppen-Geiger climate classification, Mandalay exhibits the equatorial winter dry climate (Climate Aw) (Kottek et al., 2006). In the typical weather year, the annual average temperature of Mandalay is 26.9°C, the average daily highest temperature in the hottest month is 38.2°C in April, and the annual average relative humidity is 68%. From 1981 to 2010, Mandalay ranked third for the maximum temperature range greater than 40.0°C in Myanmar, with a record of 324 days in April, 171 days in May, and 46 days in March (Aung et al., 2017). During the 2010 heatwave in Myanmar, Mandalay reached 45.0°C, which was the highest summer extreme temperature in 64 years (Phyu, 2010). Chapter 5 presents the field case study of a modern dwelling in Mandalay.

Figure 1-10 shows the findings from using a psychrometric chart to analyse a typical weather year of Mandalay. They indicate that comfort is achieved for less than 10% of the time in a year if no passive design strategies are adopted. If passive design strategies were considered, a time within thermal comfort could increase up to 35% by adding natural ventilation for adaptive thermal comfort, and up to 30% by adding sun shading to windows. Although the percentage of a year for thermal comfort could increase by adding the use of high thermal mass coupled with night flushed ventilation and passive solar direct gain, the effectiveness of thermal mass on the indoor thermal comfort had less benefit compared to the use of shading and natural ventilation for passive cooling in Mandalay.

When the active design strategies were considered, the use of fan-forced ventilation alone was not as significant as the use of dehumidification. By combining active cooling with dehumidification, indoor thermal comfort could be maintained for more than 50% of the year in Mandalay. The psychrometric charts illustrate the unique climate attributes and their impacts on thermal comfort - particularly the use of natural ventilation, shading, high thermal mass, high thermal mass with night flushed ventilation, and passive solar direct gain with high thermal mass for Mandalay.

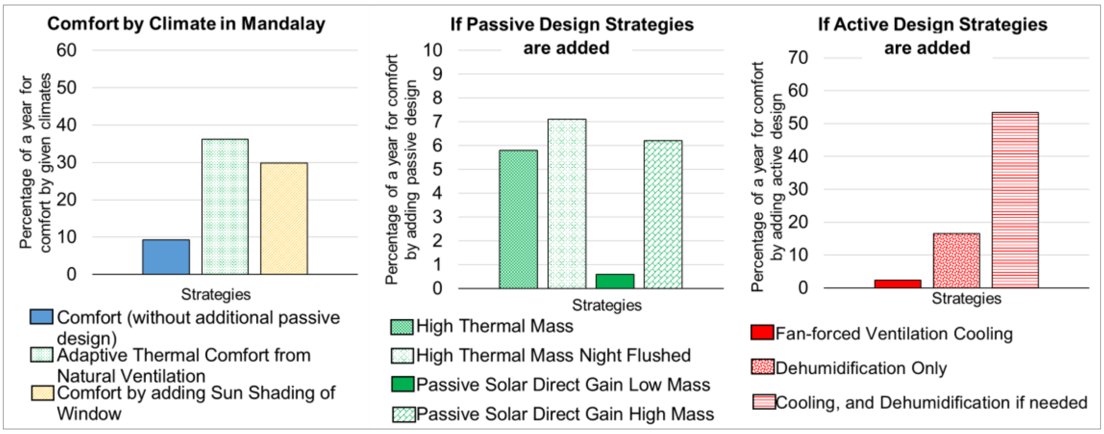

Figure 1-10. Comparison of the results of the psychrometric chart for Mandalay

Yangon: Yangon is located in lower Myanmar, about 30 km (19 miles) from the Gulf of Martaban. Formerly known as Rangoon, Yangon is the old capital of Myanmar. In Burmese, Rangoon means 'end of strife', and it was founded as a village called "Dagon" in the 6th century by the Mons. Today, Yangon is the largest city in Myanmar. According to the Köppen-Geiger climate classification, Yangon exhibits the tropical monsoon climate (Climate Am)

(Kottek et al., 2006). In the typical weather year, the annual average temperature of Yangon is 27.0°C, the average daily highest temperature in the hottest month is 39.0°C in March, and the annual average relative humidity is 79.3%. The dominant feature of Yangon is her lack of seasonal temperature variations. The maximum temperature of Yangon was 1.1°C higher in 2010 compared to 1951-60 historical data (Khine, 2015).

Figure 1-11 shows the findings from using a psychrometric chart to analyse a typical weather year of Yangon. It can be seen that comfort is achieved for less than 10% of the time in a year if no passive design strategies are adopted. If passive design strategies were considered, the duration of thermal comfort could increase up to 55% by adding natural ventilation for adaptive thermal comfort, and up to 30% by adding sun shading to windows. Although the percentage of a year for thermal comfort could increase by adding the use of high thermal mass coupled with night flushed ventilation and passive solar direct gain, the effectiveness of thermal mass on the indoor thermal comfort had less benefit compared to the use of shading and natural ventilation for passive cooling in Yangon.

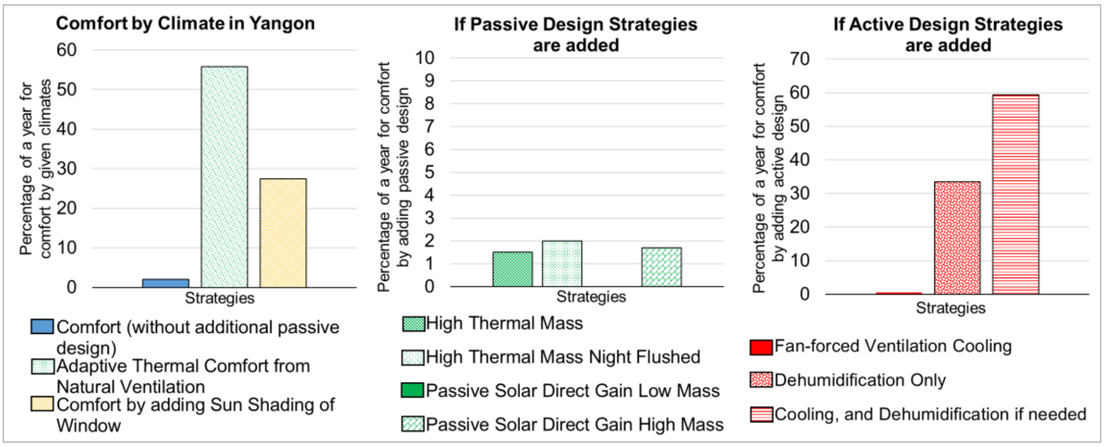

Figure 1-11. Comparison of the results of the psychrometric chart for Yangon

When the active design strategies were considered, the use of fan-forced ventilation alone was not as significant as the use of dehumidification. By combining active cooling with dehumidification, indoor thermal comfort could be maintained for more than 60% of the year in Yangon. The psychrometric charts showed the unique climate attributes and their impacts on thermal comfort - particularly the use of natural ventilation, shading, high thermal mass, high thermal mass with night flushed ventilation and passive solar direct gain with high mass for Yangon. It was also found that Yangon needs more active strategies than Mandalay and Myitkyina.

Myanmar has been experiencing global long-term climate risk (Eckstein et al., 2019), climate shift (Rubel and Kottek, 2010), changes of monsoon season, accelerated warming trends, and increased risk of extreme events. Myanmar housing might face increasing challenges due to exposure, hazard, and vulnerability to climate change; however, those effects have been not fully or systematically considered in current housing design practices for thermal comfort. Moreover, different climate zones of Myanmar could be affected differently due to their exposure to changing climate conditions, which could cause different intensities and frequencies of various hazard events. Consequently, different adaptable capacities and passive design strategies are required to reduce future vulnerability in terms of a climate-resilient pathway for building thermal performance in different cities. In this thesis, two cities (Myitkyina and Mandalay) from two climates were then selected for field measurements of two Myanmar dwellings.

1.2 Vernacular strategies for thermal comfort

Tropical weather is characterized by high humidity, high temperature, and intense solar insolation. Vernacular tropical architecture gives various design hints to modern houses. In particular, their vernacular housing practice is predominantly dependent on natural ventilation and passive cooling for thermal comfort. In the literature and practice, however, there is a gap of knowledge on Myanmar vernacular housing, specifically passive design techniques to achieve thermal comfort. The review of eight types of Myanmar vernacular houses attempted to fill this knowledge gap.

Like neighbour countries with comparable conditions, Myanmar vernacular architecture strategies have evolved to deal with excess heat and humidity. One of the most prominent strategies that can be commonly observed in Myanmar is the use of high multistage roofs (presented in Section 1.2.2) with roof ventilation. However, the Myanmar vernacular architecture does not seem to have attracted the attention of scholars and professional as much as that of other countries in Southeast Asia. Among many obstacles that have precluded it from being studied is the fact that it represents a symbolic architecture imposed by the enlightenment in Buddhism, e.g., multistage roof design. Another obstacle is the rich diversity of the country, and different customs between and within ethnic groups that have settled in Myanmar since 700 AD (Harvey, 1925), as each of these groups have reflected their ethnicity on building characteristics. Early multistage roof design in Myanmar architecture can be traced to the archaeological pieces belonging to the Pagan (Bagan) period from the eighth century (Falconer et al., 2000, Myint, 1990); thenceforth, countless buildings have been designed using various forms of multistage roofs. The use of multistage roof design seems to have remained remarkably resilient in Myanmar; however, little is known about the background of the multistage roof design and Myanmar vernacular houses. Therefore, a context of multistage roof design and their evolution in Myanmar vernacular architecture are reviewed in this section.

1.2.1 Vernacular houses

The vernacular architectural style in Myanmar is varied by the cultural influences of major ethnicities. The image shown in Figure 1-12 is from a field study of the National Races Village and a visit to the Inle lake[16] of Myanmar, which was undertaken in 2016 by the author. The National Races Village showcases eight Myanmar vernacular houses, which are replicas of significant symbolic structures characteristic of the major ethnicities residing in the country. In this section, based on the field observations, a more thoughtful analysis reveals several interesting insights, from which common features used in eight houses are discussed, despite them being found in different locations.

Built form: A gabled thatch roof and bamboo or wooden structure are found in all houses as box-like forms. Most of the building components come from off-site fabrication and are assembled as a portable structure. The main

[16] Inle Lake is in the Shan Hills of Myanmar. In the unique watery world of Inle Lake, Intha fisherman row canoes with one leg, gardens float, and wooden homes perch above the water on rickety stilts.

houses are raised above the ground on a series of posts. An open space under the main house is either under-used or used for domestic animals. Houses are either one or two-storey dwellings with a backyard and are rarely multi-storey. Room span and column spacing vary from 2 to 3 metres (7 to 9 feet). Family lifestyle patterns are usually reflected in the building size and building plan, which could serve either nuclear or extended family models. One notable feature in the Kachin house and the Chin house (Figure 1-12) is the open porch that is used for a wood-burning fireplace in the winter, as these two groups mainly live in mountainous regions. Another distinctive feature in the Kayah and Chin house is the use of a hipped roof.

Building material: Vernacular buildings in Myanmar are often assembled with natural, rustic, unpainted wooden or bamboo envelopes and thatch roofs. Walls and floor have low thermal mass so lightweight in construction with highly permeable external walls is beneficial for small diurnal temperature ranges. Some houses are painted with a dark colour coal tar epoxy. That paint makes the house vulnerable to fires, and increases solar heat gain; however, it also protects from the weather (i.e., rain) and extends the lifespan of structures. In the past, brick is rarely used for envelopes, but it is used for the foundation of the main posts.

Roof, eave and gable vent: Thatched roofs bring insulation benefits to prevent intense solar radiation, and are combined with ventilated attic spaces. Eave projections are the main shading device in Myanmar houses that prevent heavy rain and allow no obstructions to ventilation and daylighting. The roof space is unoccupied as a consequence of the high internal air temperature near the roof surface. One notable feature in the Bamar house (Figure 1-13) is its use of gable vents on the pediment and voids in wooden wall carvings, facilitating air exchange. Similar ventilation details can be found in Commander-in-Chief Minister Kinwun Mingyi U Kaung's house (Sein et al., 1970a).

Raised floor and veranda: Raised floors have several functions: to protect against flood, prevent moisture penetration from the wet ground, to allow the house to be ventilated through cracks in the raised floor, and to offset the radiated heat gain from the hot-dry ground. Any gaps between different floor levels facilitate fresh air inflow. A veranda, whether narrow or large, provides some shelter and a buffer space for the main house from direct sunlight.

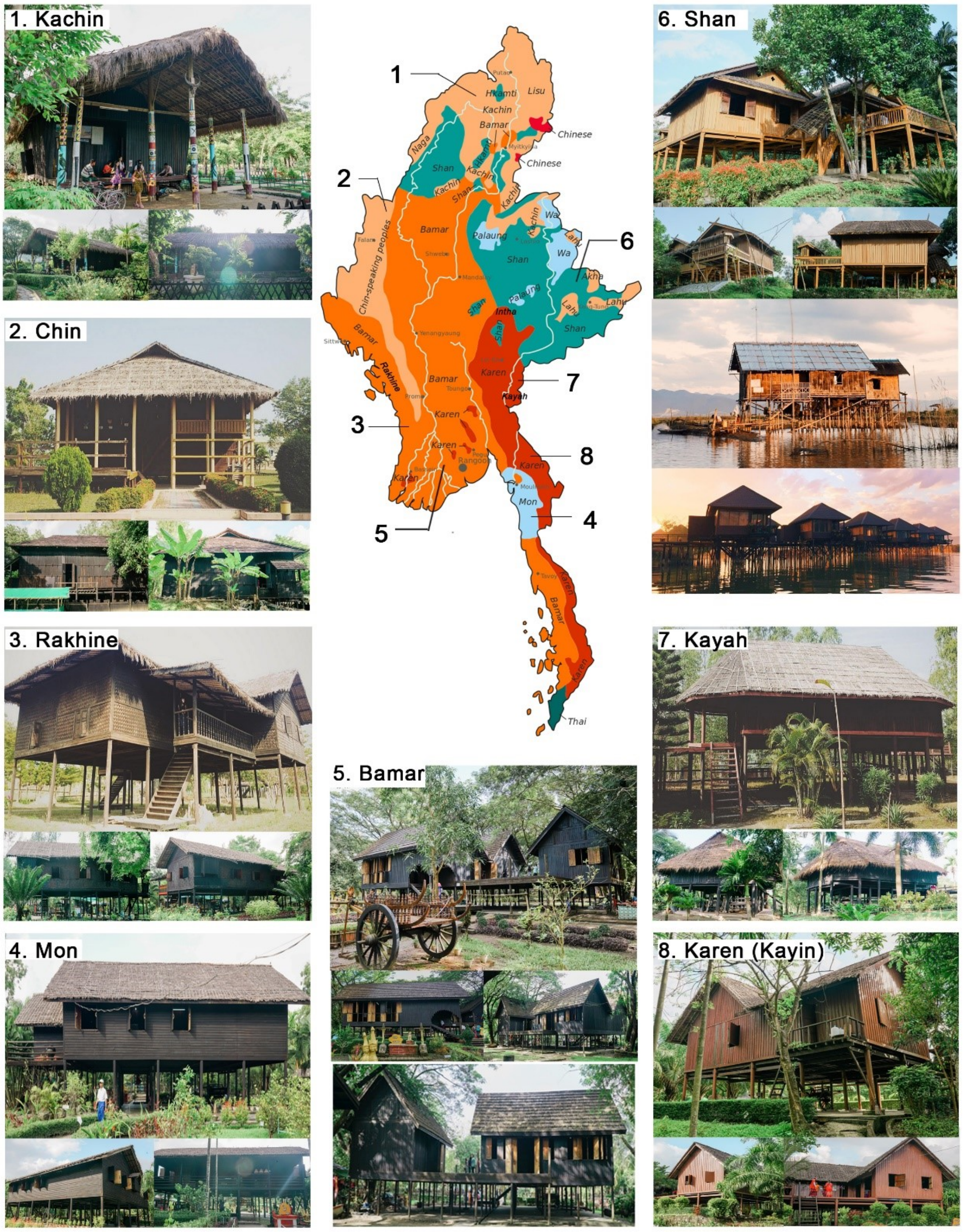

Figure 1-12. Ethnolinguistic map of Burma 1972 (Laoi, 2014) and Myanmar vernacular house types (Zune, 2017b)

Layout: Building layout is strictly regulated by tradition, with a hierarchy based on gender and age. Window locations are on either side of the building; some rooms are unlit, as most traditional livelihood activities are carried on outdoors. The internal walls provide privacy; however, they are not fully attached to the roof. Ceilings are rarely built; therefore, gaps between the top of the walls and roofs allow natural light through the gable vents.

Ventilation and infiltration: Protection from strong winds and preventing the growth of mould is a priority in Myanmar housing. Therefore, ventilation design is necessary to provide complex functions for structural stability, health concerns, and thermal comfort. Besides the heat gain protection by means of roof shading, thermal comfort in all Myanmar vernacular houses tend to achieve by employing several openings for cross-ventilation. Due to cultural influences and safety requirements, the windows and door openings function in different modes daily. Gable vents and openings between the roof and wall sections provide cross-ventilation and buoyancy-driven ventilation to remove smoke from cooking and hot air from houses, although windows and doors are closed. Locating at a similar distance from the Equator, most Myanmar vernacular houses are very similar to Amazon Yagua houses (Coch, 1998) and Southeast-Asian vernacular houses (Taylor, 1982).

Apart from the above-mentioned common characteristics, different passive design techniques used in the Bamar and the Mon houses are presented here. The Bamar, the largest group in Myanmar, originally lived at the centre of Myanmar under the equatorial winter dry climate zone. The climate has a severe dry season, and a short but extremely rainy wet season. In the Bamar house [Figure 1-13(a)], all rooms are small and located above-raised floors. The roofs are broken down into small units with overlapping roofs that reduce roof height and roof size. The roof shading and roof ventilation techniques are similar to the north-east Indian houses (Singh et al., 2009) that facilitate allows the removal of buoyant hot air, even when the wind is still. Windows are tall and windowsills are closed to the floor; therefore, ventilation directly goes to the floor seating space. A separated kitchen is connected by an open deck.

The Mon, one of the earliest people in Indochina, originally lived in the southern part of Myanmar, where the tropical monsoon climate zone has a less pronounced dry season and an extraordinarily rainy wet season. In the Mon house [Figure 1-13(b)], there is a large entrance veranda with a central staircase that sets back the main house, to avoid direct solar heat gain and wind-blown rain. Although there are fewer window areas and no gable vents in the Mon house, hot air can be removed by cross-ventilation through an elongated, rectangular layout. A kitchen is attached to the main house; therefore, it is convenient to access when it is raining.

In light of this overview of traditional houses, a combination of various building components for passive design techniques is ideally suited to maintain thermal comfort for the related tropical contexts. However, the movement of people throughout the country leads to the sharing and mixing of building styles (Falconer et al., 2000), and the effect of passive design for thermal comfort might vary by regional climate contexts. Thus, it is important to investigate the impacts of various combinations of building components (e.g., in terms of orientation, window-to-wall ratio, building size, and layout) on indoor thermal performance according to the three Myanmar climate zones. For which, Chapter 3 presented the thermal performance of vernacular houses in Myanmar with simulation experiments.

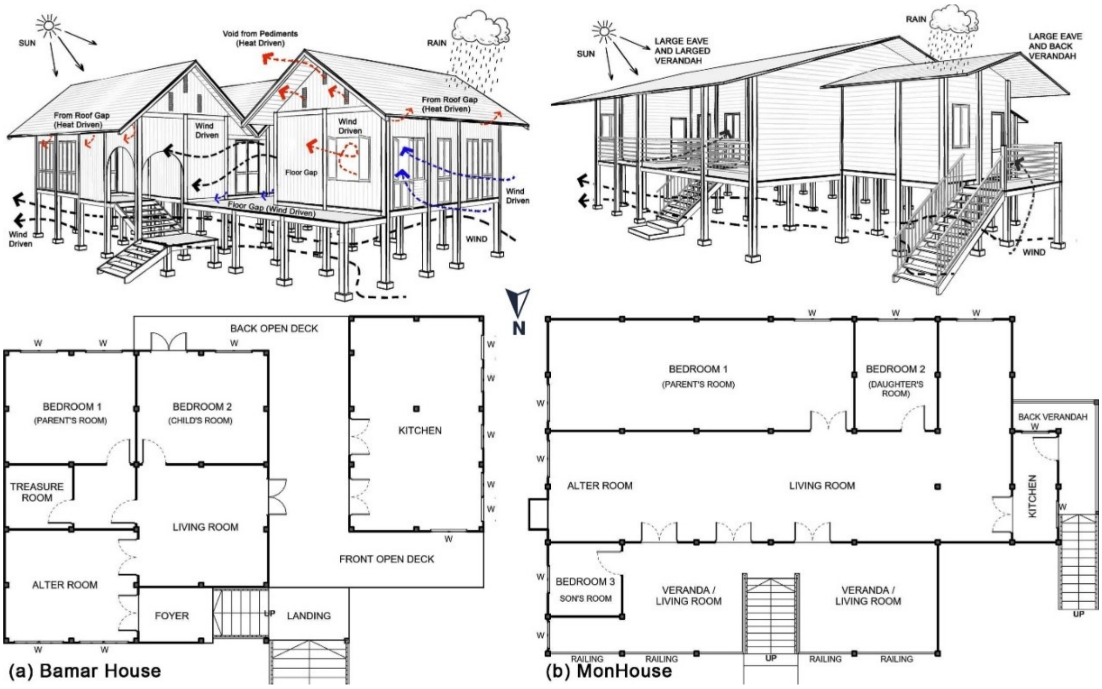

Figure 1-13. Built form and plan of Bamar house (left) and Mon house (right) in the study (Zune, 2017a)

1.2.2 Myanmar traditional roof design

The multistage roofs are known as "*Pyatthat*"[17] in Myanmar. Their use was initially restricted by the sumptuary laws to religious buildings for the continuity of the Buddhist tradition and the royal family; that context typifies a close link between Buddhism and kingship in forming the cultural heritage of Myanmar (Falconer et al., 2000, Fraser-Lu, 1994, Myint-U, 2008, Sein et al., 1970b). Multistage roofs, which are dominant features of Myanmar's ancient traditional buildings, are made of successive gabled rectangular roofs in an exaggerated pyramidal shape that consists of a series of tiers (Sein et al., 1970b). The form is a fixed kind of 'parasol' concept; therefore, a roof can be thought of as a broad umbrella over the occupied spaces. The use of an abstract roof curve defines the shape of multistage roofs to divide the number of tiers. The number of tiers in the buildings with multistage roofs represents Buddhist cosmology – the description of the 31 planes of existence. The centre of multistage roofs is recognised as the hallmark of a building – a place for either the image of the Buddha or the throne room of a king (Myint, 1990, Sein et al., 1970b). An intermediate box-like roof structure inserted between each tier is called *Le-baw*, where gable vents are added for roof ventilation for the stack strategy for thermal comfort. The total building height, including the height of the raised floor and the crown of the multistage roofs, varies between 1.25 and 2 times the length or width of the building. Four types of multistage roof, shown in Figure 1-14, are categorised by historical dynasties[18] (Myint, 1990).

From the fifteenth century Bargayar monastery [Figure 1-14] to the eighteenth century Mandalay palace and Myadaung monasteries [Figure 1-15], most of

[17] Pyatthat in the Pali-Myanmar dictionary means 'a building with a series of roof tiers'. The word originated from the Sanskrit word 'Pa-Thar-Da', which means 'a building with pleasant sight.' Each tier is called "boun'', and the numbers are always uneven to keep three or five or seven tiers, up to eleven. An intermediate box-like roof structure inserted between each tier is called "Le-baw".

[18] Four types of multistage roofs can be categorised by historical dynasties: Pagan dynasty, first-Ava dynasty, Hanthawaddy dynasty, and Konbaung dynasty. The use of intermediate roof structures is more dominant in the Pagan and first-Ava dynasties. The use of a series of roofs is more powerful in the Hanthawaddy dynasty, which was developed for Kho-Nan-Cho design, which means there are the same length and width at every corner. The empire of King Bayinnaung extended to the Ayutthaya of Thailand in the Hanthawaddy Dynasty. Therefore, the use of a series of roofs has been developed in both countries.

the surviving buildings with multistage roofs can be found around Mandalay (Falconer et al., 2000, Sein et al., 1970b). Towards the end of the eighteenth century or in the early nineteenth century, several changes in the buildings with multistage roofs could be observed due to the impacts of socio-economic and political conditions. For instance, a colourful Italianate façade, further uplifted by tiered teak roofs, is one of the finest examples of brick and plaster monasteries [Figure 1-15], showcasing changes in building technology with the novel forms of cultural expression in the 1930s (Falconer et al., 2000).

Today, the traditional tiered roof features of Yangon city hall (Bansal et al., 2015), the concourses of Bagan Airport and the Naypyidaw Parliament building (Hluttaw Brochure Working Group) represent the use of multistage roofs as memorable treasures of Myanmar traditional architecture. The Karaweik Hall palace (Falconer et al., 2000) and the elaborate wooden resting pavilion in the Novotel Mandalay hotel (Falconer et al., 2000) represent multistage roof-inspired building forms as an echo of Myanmar architecture. Kandawgyi Palace Hotel, completed in 1996 by a Thai Architects firm (Falconer et al., 2000), reveals the sharing concept of a series of roofs between Myanmar and Thailand as contemporary architecture. It also can be seen that the relics of building form remain up to the present day as both traditional and contemporary architecture, and their presence represents material fragments of historical reality.

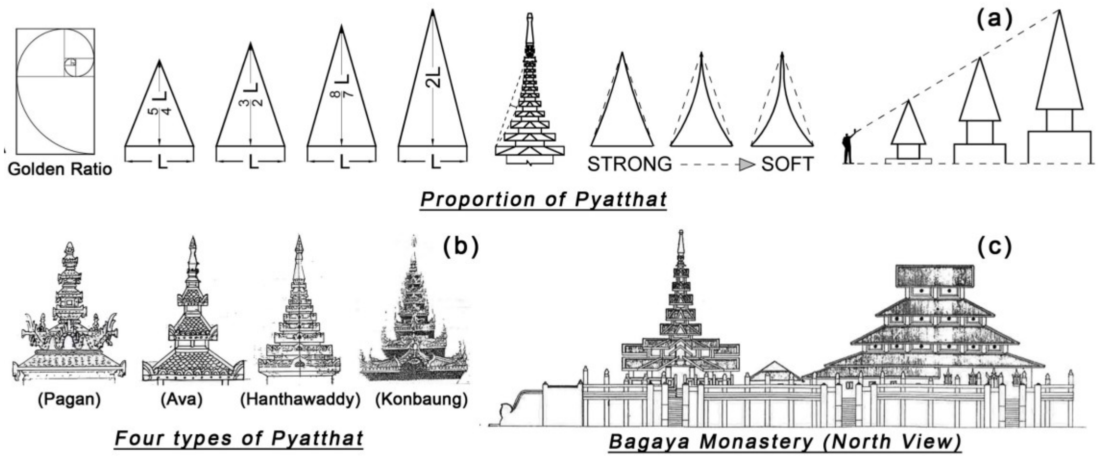

Figure 1-14. (a) Proportion of Pyatthat (b) Four types of Pyatthat (Myint, 1990) (c) Bagaya monastery in Mandalay (completed in 1593) (Sein et al., 1970b)

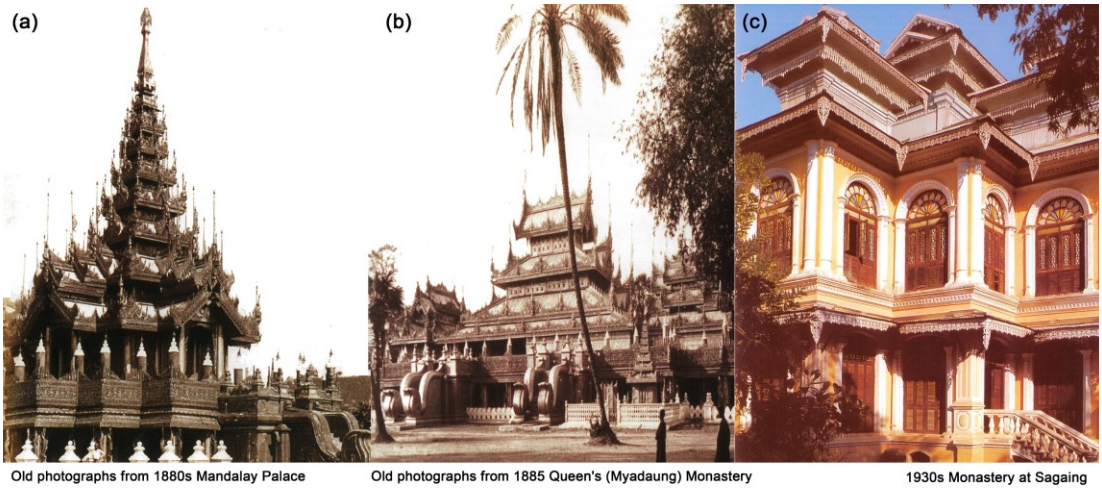

Figure 1-15. (a) Mandalay Palace in the 1880s; (b) Myadaung monasteries in 1885; (c) Monastery at Sagaing in the 1930s (Falconer et al., 2000)

Figure 1-14, Figure 1-15 and Figure 1-16 show that there have been several changes in forms and use of materials in Myanmar's traditional buildings with multistage roofs over time. Original thatch and timber shingles have become metal roofs, and timber walls and raised timber floors have become brick walls and concrete floors. Open corridors along with the perimeter of the building were often lost due to the constraints of the gross floor area. The numbers of the occupied storey have increased, and the height of raised floors was lost. Despite the changes, the multistage roofs in Myanmar's traditional buildings have stayed remarkably resilient.

Figure 1-16. The use of multistage roof in Myanmar architecture (Bansal et al., 2015, Falconer et al., 2000, Hluttaw Brochure Working Group, 2017)

Vernacular architecture strategies are microclimate modifiers (Soflaei et al., 2016). The combination of the indoor microclimate and the surrounding microclimate is considered to be an extension of the indoor climate (Du et al., 2014), which is the building microclimate. Spaces, which are connected either horizontally or vertically are, therefore, building microclimate modifiers. Elevated naves in the stave churches (Bakken, 2016) and roof spaces in Myanmar's traditional buildings with multistage roofs, as shown in Figure 2-1, can be counted as one type of building microclimate modifier. Although the size and use of the buildings with multistage roofs are not directly applicable to the design of Myanmar housing, both represent the fundamental knowledge in the understanding of Myanmar architecture regarding stack strategy passive design approach for building thermal comfort. Bridging this knowledge was the background aim of this section. For instance, it is important to investigate how the changes in roof typologies, roof height, roof ventilation and building materials affect building microclimate for thermal performance of a building with a multistage roof.

In Figure 1-17, a comparison between three roof typologies with the same internal volume but varied roof height is shown. Building (a) has a combination of hipped-roofs and multi-tier roofs [Figure 1-17-a] distributed on four sides, and the shape of the roof dictated the height and indoor air volume. In order to keep the same internal air volume as in building (a), in the building (b) a combination of multi-tier and offset gable roofs were used to reduce the roof height and increase the width [Figure 1-17-b]. In the building (c) [Figure 1-17-c], if the same length of the intermediate roof structures was kept, it was necessary to reduce the height of the roof in order to maintain the same internal air volume. The use of intermediate roof structures in the building (b) and (c) is not as significant as their use in building (a). This simple comparison also indicated that the investigation of various practices in roof typologies is, indeed, a wide scope of work.

There is reason to acquire a comprehensive understanding of Myanmar traditional buildings with multistage roofs as they are Myanmar cultural hyper-complex character and contain broader and in-depth details of passive vernacular design. That will be for further research. In this thesis, one obvious investigation can be done by comparing a building with multi-stage roofs

[Figure 1-17-a] and a building with a single gable roof. Then, the impacts of roof ventilation, roof height and the use of intermediate roof structures on the thermal performance can be investigated using stack strategy. Chapter 3 presented these objectives.

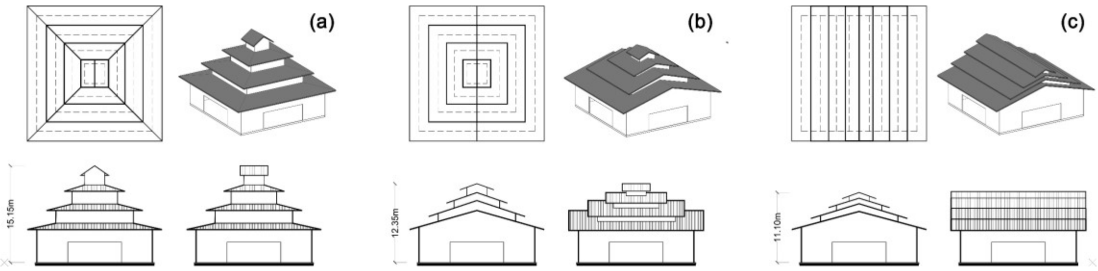

Figure 1-17. Building with multistage roofs (a) hipped roofs and multitier; (b) offset gable roofs and multitier; (c) same length gable roofs and multitier

1.3 Building design evolution

The practices of vernacular housing seem to have remained remarkably resilient in Myanmar, although the types of materials used have changed (Bansal et al., 2015, Falconer et al., 2000). In the context of building thermal performance design, the proportion of rural and urban living is essential for housing design consideration due to the effect of the urban heat island (UHI). Census results show that 70% of the population live in rural areas, and 30% live in urban areas in Myanmar as a whole. On the state level, in Yangon, 70% of the population live in urban areas, and 30% live in rural areas; in Mandalay, 35% live in urban areas, and 65% live in rural areas; and in Kachin (in which the studied city Myitkyina is located), 36% live in urban areas and 64% in rural ones (Ministry of Labour, 2015). The patterns of land change and their potential impacts on land surface temperature change (LTS) in Yangon revealed that there are seasonal temperature and nighttime temperature differences between 2000 and 2015, and there are warmer temperatures in 2015 (Yi-ChenWang et al., 2018). Therefore, the effect of urban heat island can be expected to vary between the three cities, reflecting varying urban density. In addition to those quantitative facts, another important issue germane to Myanmar housing is the impacts of post-colonialism and globalization on housing design, warranting investigation of:

- The challenges of vernacular design elements in the changing climate conditions, and why some of them have been lost.

- The drivers that introduce modern customs and how they change building design.
- The objectives of building thermal performance that underpin all current and future housing in Myanmar.

Means of addressing these issues can be complementary. Investigating the differences between Myanmar vernacular housing in the past and the present conditions, particularly the new approaches in housing which bring diverse design for the countryside and urban housing, will help to support further consideration in the achievement of building thermal resilience design for changing climate conditions. Therefore, building design changes in Myanmar during the 19th to 20th century is reviewed in the following sections.

1.3.1 Buildings in the 19th century

In the 19th century, housing in Myanmar was witnessing new ways of living from European residents in Myanmar and an indigenous Eurasian (Anglo-Burmese) community. New modes of detached house design had begun to emerge, manifesting colonial and European influences on living, changing building forms and building plans in Myanmar and India. In the Anglo-Indian milieu of domestic life in the 18th century (Grant, 1862), the building form was changed from the native peasant Indian bungalow[19] [Figure 1-18-a] to a colonial bungalow[20] [Figure 1-18-b]. The photo of the first permanent foreign embassy at Mandalay in 1868 (British Library, 2020) showed that the British residency in Myanmar was similar to a combination of Bamar and Mon houses, rather than a bungalow for Anglo-Indian domestic life.

[19] The centre square may consist of either one or two apartments, according to the circumstances in a Bengali banggolo (bungalow), whilst the thatch roof extending considerable over all sides that is supported at the extreme edges upon bamboo or wooden pillars, thus forming a covered veranda around the building.

[20] For European residents, improving upon a Bengali banggolo, the veranda is enclosed by erecting either a mat or brick wall, and in like way, throwing partitions across the corners, converting the veranda into little rooms for the convenience either of themselves or visitors. The roof being carried beyond these, as before, would complete nearly all that exists in the European bungalo of the present day.

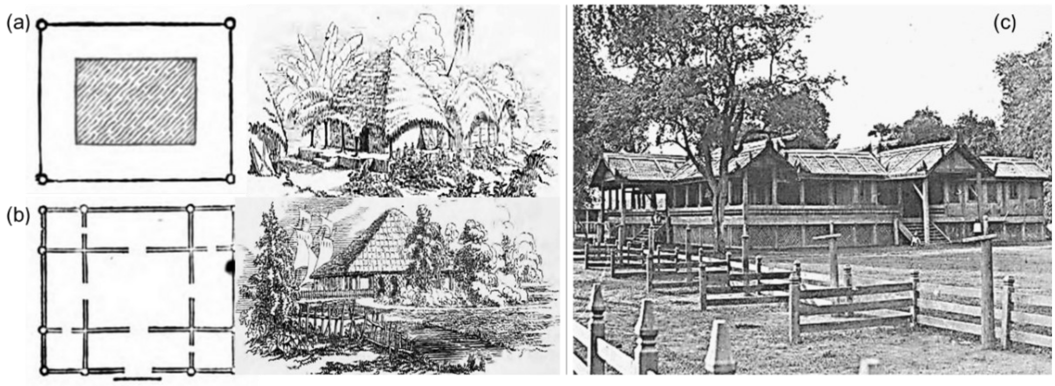

Figure 1-18. (a) Native Indian bungalow; (b) Bungalow for Anglo-Indian domestic life (Grant, 1862); and the first permanent foreign embassy and the British residency at Mandalay in 1868 (British Library, 2020)

The use of fragmented building plans with rooms and circulation spaces can be seen in Bamar and Mon houses [Figure 1-13], whereby either British residents or their visitors might meet their needs for convenience and privacy at a permanent foreign embassy. Therefore, they might initially decide to maintain several tropical vernacular elements, such as lightweight building envelope with a raised floor, and the roof implementing large eave projections for roof shading, with the building setback for the main house, with the use of veranda to adapt the local climate realities [Figure 1-18-c], instead of bringing new ideas to their residence.

1.3.2 Buildings in the 20th century

The buildings of the late 19th and early 20th centuries, a century following the First Anglo-Burmese War in 1824, the colonial influenced building typology in Myanmar underwent significant development in architectural style and adjustment to local conditions. For instance, the Pegu Club[21], which was the most exclusive British club in Burma, showed a contemporary representation of multi-tier roofs in 1910 (Bansal et al., 2015). The high ceilings and carriage porch of the Pegu Club show clear signs of elevated social status, whilst the main building used louvred doors and windows to allow for cross-ventilation [Figure 1-20-a] (Bansal et al., 2015). The Governor's Residence was built entirely of Burmese teak, and this two-storey structure admirably represents a

[21] The Pegu Club was a sprawling double-storey building with a bar, billiards room, tennis and squash courts, and many rooms occupied by workers and single people; it was not really for families.

classic phase of pre-independence Yangon architecture in which vernacular elements blended with colonial Victorian design to produce impressively proportioned villas [Figure 1-20-b] (Falconer et al., 2000). These examples revealed that the British colonials brought new ideas to the buildings with a rich infusion of diverse decorative vocabularies from the novelty of Victorian and Edwardian design idioms to Myanmar. Instead of the faux and false type of balconies and charming ironwork balcony type common in Western buildings in Europe from this period, a large portico with deep eaves, balconies, or veranda was used in most colonial influenced housing. Initially, the changes seemed to be a foreign aesthetic, and gradually they were as well-established as a local tradition by adapting the local climate realities, manifesting a new kind of collective and a new kind of housing design.

Semi-puka mansions such as Miraflores semi-pukka mansion [Figure 1-20-c] and Daw Khin San Yin's house [Figure 1-20-d] feature extensive use of high ceilings, full high louvre windows, stained glass, and Marseille roof tiles (Henderson and Webster, 2015). While the traditional raised floor, gable vents, and openings between the roof and wall sections had faded away by the time of the above-mentioned buildings (in major projects), a full high window acted as a powerful auxiliary, and a high ceiling with multistage roofs acted as an alternative source of cross-ventilation. The use of cupolas was introduced in Daw Khin San Yin's house rather than using traditional multistage roof inspired roof design like Miraflores. 54 University Avenue[22], a colonial-era villa [Figure 1-20-e] (Wikipedia, n.d), showcases that the use of full high louvre windows and high ceilings had faded away by the mid-20th century. Another example might be U Thant's house[23] [Figure 1-20-f] (UThantHouse, n.d), characterized by more extensive use of brick walls and small windows compared to other buildings. Unlike the buildings shown in Figure 1-20, some buildings in the Shan Hills of Myanmar have duplicated versions of Scottish cottages rather than a mix between Myanmar vernacular house design and European building

[22] 54 University Avenue is a house in Bahan Township, Yangon. It is the residence of Aung San Suu Kyi, a Burmese politician and the incumbent State Counsellor of Myanmar.

[23] U Thant was a Burmese diplomat and the third Secretary-General of the United Nation from 1961 to 1971, and the first non-Scandinavian to hold the position.

design. Besides changes in construction materials and ventilation approach for thermal comfort, many European building elements such as a fireplace, pebble-dashed walls, recessed porches, and lavish decorations were used that were completely alien to Myanmar housing at that time.

Figure 1-19 Pegu Club postcard in 1910 and present-day (Bansal et al., 2015)

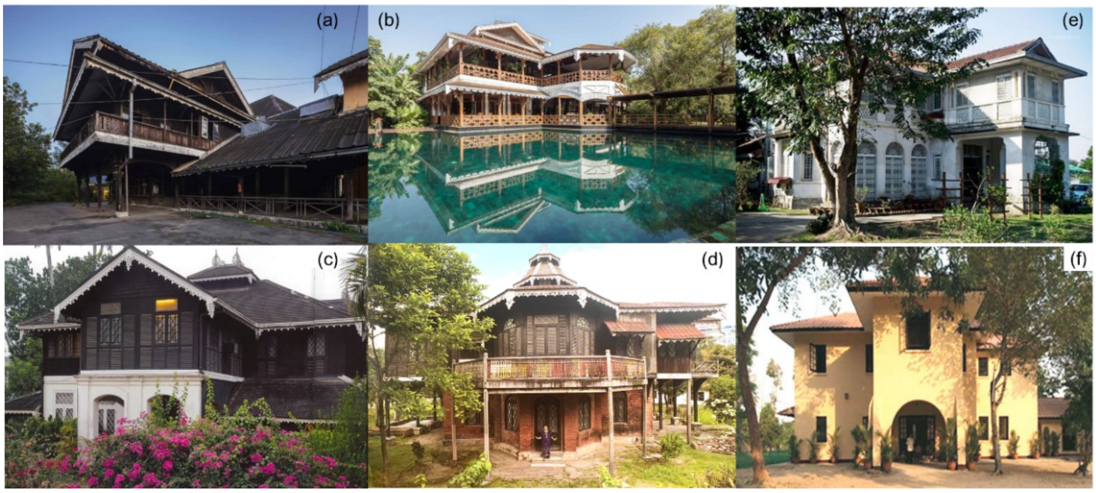

Figure 1-20. (a) Pegu Club built in c.1882; (b) Kayah State Governor's Residence built in c.1920; (c) Miraflores or Tin Mar Yi's Melody semi-pukka mansion built in c.1891; (d) Daw Khin San Yin's house built in c.1902; (e) 54 University Avenue; and (f) U Thant (Secretary-General of the United Nations) house (Bansal et al., 2015, Falconer et al., 2000, Henderson and Webster, 2015, UThantHouse, n.d, Wikipedia, n.d)

Aside from buildings for colonial civil servants and the Anglo-Indian and Anglo-Burmese communities, most Myanmar houses continued to exhibit traditional vernacular practices until the mid-20th century. Eight types of Myanmar vernacular houses, shown in Figure 1-21, exhibit similar built forms but different roof designs, some of which are rarely seen nowadays. The detached house in central Myanmar is perhaps the most common general type seen everywhere across the country, deploying lightweight building materials with shading from well-established trees, to moderate the central dry zone's extremes. On the contrary, the picture of the home of the large fishing village located on the coastline of the lower Myanmar shows a vernacular house design similar to that mentioned in Section 1.2.1, but heavily constructed to withstand strong winds and wave surges.

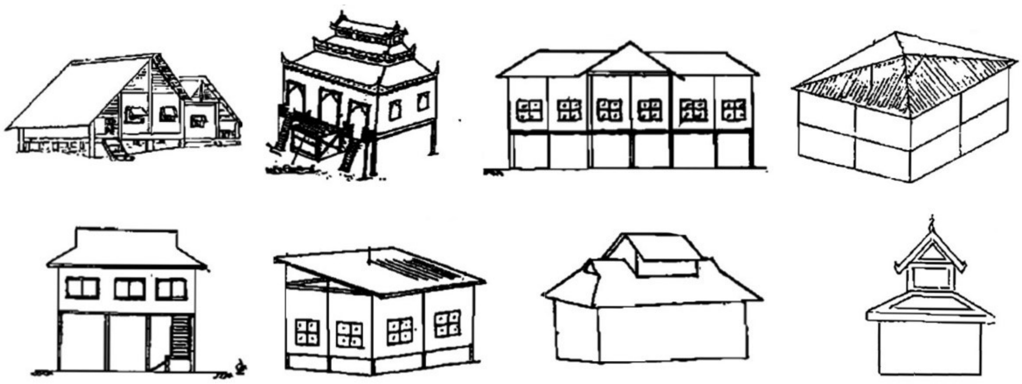

Figure 1-21. Myanmar vernacular house types (Hlaing, 2000)

Unlike the Bamar and Mon houses, the country gentleman's mansion shown in Figure 1-22 (c) represents Myanmar traditional housing of the late 20th century, showing changes in building forms and plans. The building is a three-tiered, woodpile construction. The ground floor serves as a public area containing the guest reception room, dining room, and kitchen. Tall, louvred doors open to allow for cooling during the hot days but are secured tightly at night. Spaces of all personal activities are on the second floor, including the altar and meditation room. A prominent roof shields the house from heavy rains, and the multi-level design allows for greater air circulation. Indeed, some vernacular design elements, such as the raised floor, lattice frame of split bamboo or timber walls, have been lost in country gentleman's mansions and other Myanmar houses throughout the country. A review of colonial influenced buildings and Myanmar houses in the 19th – 20th centuries reveals that changes in Myanmar housing design for thermal comfort are not a matter of using vernacular practices presented in Section 1.2, but a combination of different passive design strategies to suit the local climate contexts. Therefore, some vernacular practices still have survived in Myanmar for centuries because of their capability to redefine themselves and to adapt in response to new cultural realities and socio-economic conditions.

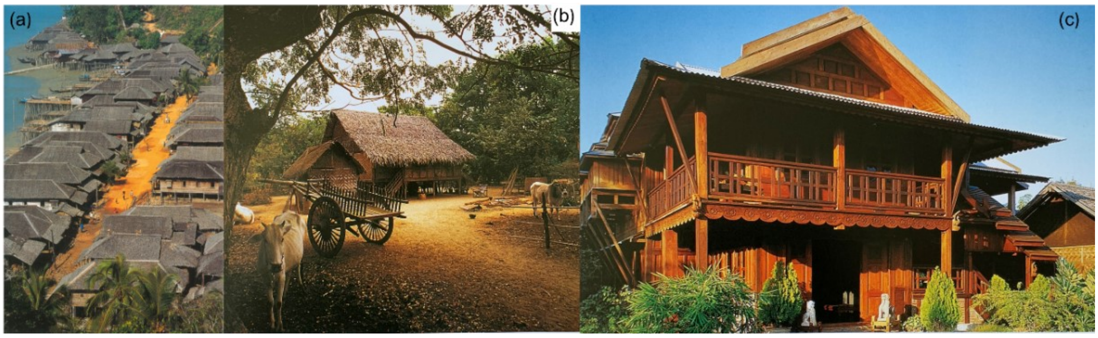

Figure 1-22. (a) Fishing village in lower Myanmar; (b) a detached house in central Myanmar (c) A country gentleman's mansion built in 1996 in Bagan, central Myanmar (Falconer et al., 2000)

1.3.3 Modern customs

As buildings in Myanmar have a high risk of earthquake, the Myanmar Engineering Society suggests the basic design requirements; in Figure 1-23, there is a practice in using thin brick walls (4.5 inches) without roof insulation. Eight Myanmar vernacular house types [Figure 1-21] and the picture of a fishing village in lower Myanmar [Figure 1-22] are illustrative of the fact that the majority of Myanmar houses were built as single, detached houses, but since the late 20th century there has been an increasing number of multi-storeys buildings in Yangon and Mandalay. A study, which utilized a series of hypothetical generic building forms in diverse spatial configurations in a fixed built density and site, found that clustering-weighted compacity is a better predictor of the annual cooling energy use intensity in tropical climate than both compacity and annual cumulative envelope solar radiation incident energy (Zhang et al., 2015). Detached houses are therefore distinct from multi-storey buildings in terms of their energy demand, thermal performance, and passive design techniques; that is important in defining the scope of work for this thesis.

This thesis was mainly focused on detached house types, which have been commonly built in Myanmar. Even for detached houses, changes in Myanmar houses from their vernacular architecture to the 21st-century buildings are not uniform, but the impacts of modern customs in Myanmar housing in terms of their thermal performance design in the present climates must be studied using a simplified and archetypical building form, as shown in Figure 1-22b.

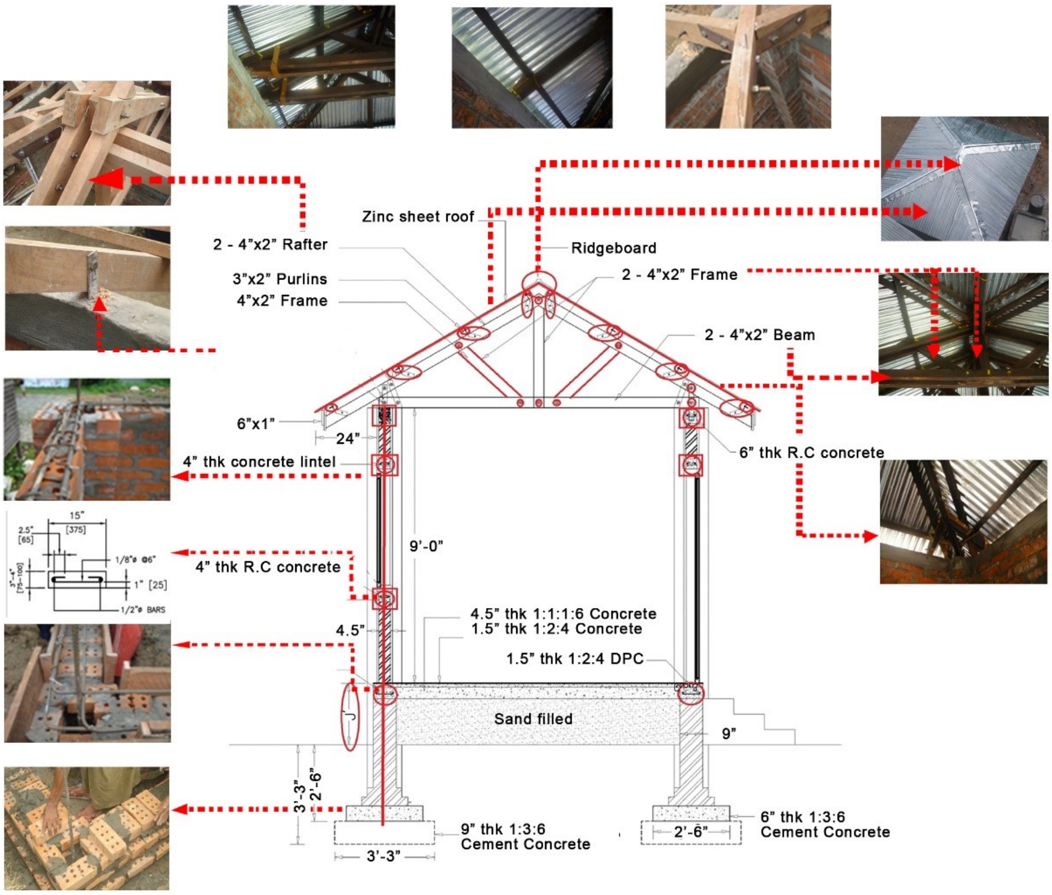

Figure 1-23. Earthquake design requirements for a detached house in Myanmar, translated from Myanmar Earthquake Committee (n.d)

In this case, from the review of Section 1.2, changes can be considered as follows -

- *Building material:* Brick walls, concrete floors, glazed windows, and zinc or other metal roofs have become alternative choices for modern materials. Also, the presence or absence of the raised floor should be considered in terms of building form changes.
- *Gable vents and ceiling:* The presence and absence of gable vents and ceiling can affect cross-ventilation and buoyant ventilation. Consequently, if there are gable vents, ceiling voids can be created on a flat false ceiling to remove buoyant hot air, and to prevent radiated heat gain from zinc or other metal roofs.
- *Infiltration:* Changes in building materials have a significant effect on building infiltration. In order to achieve some degree of air change

without adding windows and voids, a new method was necessary to introduce brick houses. For example, one of the popular aesthetic components for brick houses in Southeast Asia is the use of ventilation blocks, which are perforated concrete blocks, for walls and fences (Schatz, 2014). Ventilation blocks facilitate airflow even when windows and doors are closed.

Table 1-2 lists modern customs in Myanmar vernacular housing that vary in terms of building materials, the presence or absence of a ceiling, gable vents, ceiling voids, and ventilation blocks. As the thermal comfort in vernacular housing can be varied by its use of vernacular and modern construction materials (Samuel et al., 2017), it is important to investigate the thermal performance of modern customs for current and future climate conditions. In addition to the 15 types of Myanmar vernacular houses shown in Table 1-2, the impacts of building sizes and floor arrangements on indoor air temperature can be investigated by comparing Bamar and Mon houses, as shown in Figure 1-13. Chapter 3 attempted to compare the impacts of the vernacular practices and modern customs on building thermal performance of Myanmar housing.

Table 1-2. A possible combination of building components in Myanmar vernacular housing

	Roof	Wall	Window	Floor	Gable vent (Y/N)	Ceiling (Y/N)
1	Thatch	Timber	Timber	Timber	No	No
2	Thatch	Timber	Timber	Timber	Yes	No
3	Thatch	Timber	Timber	Timber	Yes	Yes (with void)
4	Thatch	Timber	Timber	Concrete	No	No
5	Thatch	Timber	Timber	Concrete	Yes	No
6	Thatch	Timber	Timber	Concrete	Yes	Yes (with void)
7	Metal	Timber	Timber	Concrete	No	No
8	Metal	Timber	Timber	Concrete	Yes	No
9	Metal	Timber	Timber	Concrete	Yes	Yes (with void)
10	Metal	Brick	Glass	Concrete	No	No
11	Metal	Brick	Glass	Concrete	Yes	No
12	Metal	Brick	Glass	Concrete	Yes	Yes (at gable roof)
13	Metal	Brick	Glass	Concrete	Yes	Yes (with void)
14	Metal	Brick	Glass	Concrete	Ventilation block	Yes
15	Metal	Brick	Glass	Concrete	No	Yes

1.4 Conclusion

This chapter reviewed the context of Myanmar in terms of its geography, climates and vernacular housing. This chapter contributes to a novel review of passive design techniques used in Myanmar vernacular houses and traditional buildings with multistage roofs, to achieve thermal comfort based on the present climate and future climate scenarios (Zune et al., 2020a, 2020c, 2020d). In light of the risk triangle and predicted future climate scenario, Myanmar is anticipated to experience warmer and drier winters, hotter and more extreme summers, and more rainfall during a shorter monsoon time. These effects will probably continue to be felt for decades, and all these changes are inevitable. All the predictions and observations of climate shift, population growth, and deforestation are likely to be immense and will play out in multi-dimensional ways in Myanmar, with fundamental implications for housing requirements.

Tropical climate zones are found in the regions between the equator and the tropics, where the general patterns of the climates are typically frost-free and warm, and where humidity is variable depending on the precipitation pattern. Sunlight is intense in the tropics, and the intensity of diffuse solar radiation is high. The tropical vernacular architecture employs natural ventilation and sun protection in order to respond to these climatic characteristics for building thermal performance. It was discussed the context of passive design used in Myanmar buildings from eight Myanmar vernacular houses and Myanmar's ancient traditional buildings. Deep overhangs, pitched thatch roofs with high insulation in the roof and veranda allow a building to buffer the direct solar heat gain. Raised high floors help to increase airflow around and under a building, and highly permeable building envelopes with lightweight timber and bamboo walls offer improved ventilation. A number of windows, including gable vents, are typical tropical vernacular design features. Myanmar vernacular houses are similar to many Asian vernacular houses (Lim, 1987). Vernacular architecture is recognised for its strength and adaptation, blending buildings into various settings (Foruzanmehr and Vellinga, 2011, Gallo, 1994); however, their performances have not been measured but simply experienced. However, whether Myanmar housing can deliver thermal comfort for the present and future climate scenarios is an alarming question to identify whether they are inherently vulnerable to overheating risks due to the pervasive threat of the climate crisis.

Some passive cooling design techniques (e.g., thatch roof with high insulation) have demonstrable utility, but they have been lost in modern practices (e.g., a reflective metal roof, which has low insulation, is used instead of a thatch roof). Modern customs in Myanmar buildings were reviewed based on drawings and photographs of buildings from the last two centuries. The knowledge gap of Myanmar vernacular architecture can be bridged by acquiring a comprehensive understanding of Myanmar traditional buildings with multistage roofs, particularly for their stack strategy. Therefore, it is necessary to investigate the effects of changes in roof typologies and building materials used in Myanmar's traditional buildings with multistage roofs, from which lesson learnt can be applied in building form and building typology design. The scope of alternative choice in building fabric materials and methods of construction are important to appreciate; however, it is hard to know which have been useful and which have the potential to enable adaptation for future climate scenarios in terms of building thermal performance.

As Myanmar has three distinct Koppen climates (Am, Aw and Cwa), the effect of variations in weather caused by climate change in Myanmar on building thermal performance need to differentiate based on significant climate differences. In sum, the review presented in this chapter highlight investigating to what extent vernacular passive design strategies and modern custom deliver comfort and reduce discomfort. Chapters 3, 4 and 5 attempted to present these objectives.

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Comfort in living is

far more in the brains

than in the back.

~ Ellen H. Richards,

from The Cost of Shelter for Efficiency, p62

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2. Thermal Comfort and Building Thermal Performance

Buildings are essentially instituted to protect occupiers from outdoor weather. The thermal performance of buildings operates on the way the building modifies the indoor thermal environment against the outdoor weather through its intimate relationship with occupiers and its building envelope design. As climate change is an unequivocal reality, we have witnessed increasingly severe risks for ecosystems and human health, particularly during heat-wave related events. The emerging changes in the earth's climate warrant innovative building designs for optimum thermal comfort. Chapter 1 presented passive design techniques used in vernacular buildings and buildings built in recent centuries in Myanmar, highlighting that there is a research gap in modern knowledge and techniques for improving building thermal performance in Myanmar housing for the present and future climate change scenarios. This chapter attempted to fill this gap.

Building thermal comfort is an outcome of the psycho-physiological aspects of human interactions with several environmental parameters. The importance of human perception of thermal comfort is a fundamental consideration, alongside actual improvements in passive heating and cooling *per se*, reflecting the maxim that "living is far more in the brains than in the back" (Richards, 1905, p62). Furthermore, subjective satisfaction with a building's thermal comfort relies on the successful use of building physics to respond to the weather outdoors, and several supplementary design features for energy efficiency. In attempting to improve building thermal performance in Myanmar housing, it is important to consider the basic principles that contribute to it. This chapter presents four sections that cover thermal comfort and building thermal performance based on tropical climate contexts.

In this chapter, the first section presents how the occupants' behavioural, psychological, and social items modified the indoor thermal environments, in the light of vernacular architecture. The section then presents the contexts of building thermal comfort with a focus on environmental parameters. The core comparisons of case studies presented in this thesis were based on the quantitative measures of indoor air temperature, wet-bulb temperature, and heat-index temperature; therefore, those parameters were reviewed based on the tropical climate context and the Passivhaus context. This review further provides the thermal comfort quantification for different thermal comfort models for different boundary conditions to develop the most appropriate approach to compare and evaluate the results of measured data and simulation studies. The third section introduces the 'Passivhaus' fabric-first standard' for tropical climate context; the Passivhaus is generally considered to be an ultra-low energy performance standard to build high thermal performance buildings. Finally, possibilities to improve building thermal performance in Myanmar housing and challenges of the Passivhaus concept in the tropics were reviewed in the last section.

2.1 Building thermal comfort in vernacular architecture

Many traditional cultures believed that the universe (including humans) is composed of the four elements of earth, water, fire, and air (Stasinopoulos, 2014), known as *Mahābhūta* in Buddhism, whereby the elements correspond to body parts: earth (body hair, skin, bone, and organs), water (blood, sweat, fat, and urine), fire and air (nutrients, metabolic processes, and breathing for respiration). These four elements collectively perform the making of our thermally and physically comfortable home for our lives. In addition to these four elements, our comfort is determined by the way we balance heat gains and losses from the environment, pertaining to clothing insulation, shading, and air movement. Besides clothing and activity, nutrition is mediated by a range of biological, climatic, cultural, and physiological mechanisms and rules that vary between ethnic groups, across cultures, and within societies, as well as over time (Lawrence, 2006, p114). Humans are homeothermic organisms with the same core temperature (either comfortable or warm or cold), which is how we define thermal sensation, which has been viewed as a result of balancing the four elements. The modern science of thermal comfort considers that it 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).

As a building acts as a third skin to protect from outdoor climates, it must respond to heat, cold, ground and sky radiation, wind, water vapour, humidity, and other stresses, and the various parts of the building may be considered environmental control devices (Rapoport, 1969). The success of building thermal comfort also depends on its mediation of the four elements. The envelope represents the earth element of the building; the building services for water supply and sanitary represent the water elements; comfort for heating and cooling represents the fire element; the ventilation design represents the air element. The four elements of Santorini architecture reveal that a similar approach has been employed in building design in Mediterranean contexts (Stasinopoulos, 2014). Also, the building thermal comfort approach in vernacular architecture shows that building thermal comfort is heavily influenced by outdoor climates, the choice of the design of building envelope, and behavioural, physiological, psychological, and social items of occupants. Table 2-1 compares the four elements for humans and buildings.

Table 2-1. Thermodynamic functions of human and buildings in four elements, [adapted from (Stasinopoulos, 2014)]

Four elements	Human	Building
Earth	Clothing, body, skin, bone, etc.	Envelope
Water	Blood, sweat, fat, urine, etc.	Building services, e.g., water
Fire	Metabolic activity, nutrition	Supplies for heating and cooling
Air	Breathing and blood circulation	Supplies for ventilation

All forms of vernacular architecture are built to meet specific needs, accommodating the values, economies, and ways of living of the cultures that produce them (Asquith, 2006, p129, Oliver, 1997). Vernacular buildings are intended to be climatically coupled to the earth and the air in an objective manner in their building physics (Roaf et al., 2005, p39). Despite variations in climates, culture, and availability of construction materials, vernacular architecture from different locations, share similarities and a great variety of passive design techniques [Figure 2-1]. For instance, the Trulli[24] house (Allen, 1969) and Beehive shape[25] houses (Baran and Yilmaz, 2018, Ozdeniz et al., 1998) are located at a 4° latitude difference and have a similar cone-shaped roof on a circular or square plan. However, different ventilation practices and uses of building materials create different microclimate modifiers for the two houses to maintain indoor thermal comfort for their local contexts. Similarly, Mali houses in Dogon Country[26] and Cameroon huts in Musgum[27] (Nelson, 2007) share similar beehive forms and homogeneous looks, but materials used and their interaction with the outdoor climates differ to maintain the indoor thermal comfort.

Likewise, both Viking Stöng[28] longhouses in Iceland (Hurstwic, 1999) and tropical Batak[29] longhouses in Indonesia (Domenig, 2008) share the same concept of longhouse shape layout and use of roof insulation, but ventilation practices differ in response to their outdoor climatic elements.

Despite 20ºC temperature differences in their annual temperature profiles, Stave churches[30] in north-western Europe and traditional buildings with

[24] The immensely thick stone walls and dome of Trulli houses create a pleasantly cool environment in the summer; however, the excess moisture in the air condenses while cooking; therefore, the inhabitants need to leave the doors and small windows open during the day to keep the interior dry and to remove the humid air inside the building.

[25] In a beehive-shaped house, the holes at the sides of each conical dome serve as chimneys and ventilation holes to remove smoke and hot air, allowing occupants to avoid indoor moisture from the sun-dried or burned clay brick envelope. Therefore, the inhabitants usually close the openings to prevent the extreme differences in the climate during the summer and winter, to maintain a comfortable indoor environment.

[26] The stone and earth architecture of Dogon Country is set against the steep cliffs of Mali's Bandiagara escarpment.

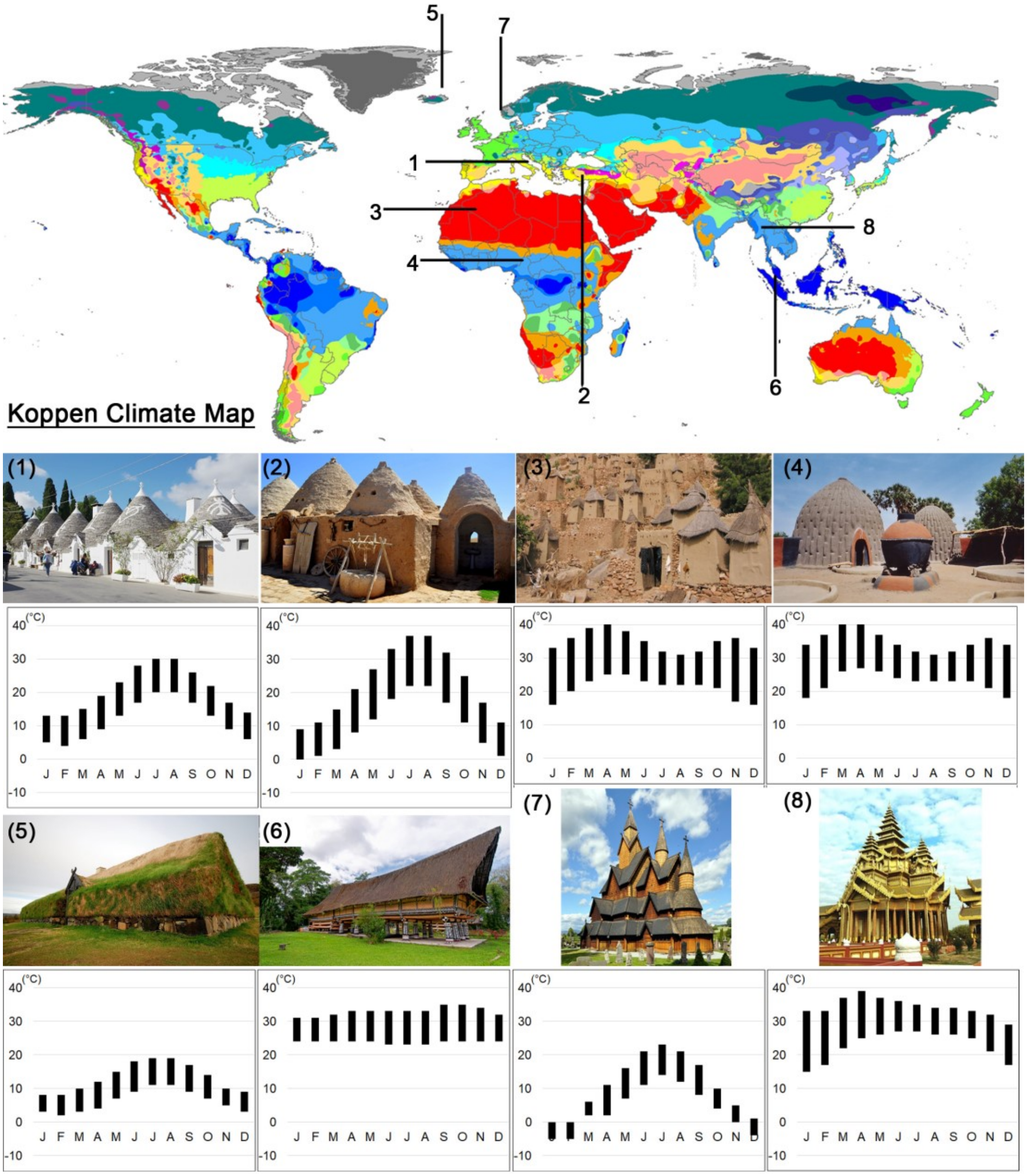
[27] Cameroon huts in Musgum are made of sun-dried mud.

[28] The Viking longhouse begins with the construction of stone footings. Besides forming a firm base on which the house rests, they also keep the wooden structural elements of the house away from the soil, protecting them from rot.

[29] The boat-shaped Batak longhouse has carved gables and a large, steeply pitched saddle back roof, with the main house built on piles.

[30] Stave churches are elaborately carved wooden houses of worship once common in north-western Europe. A stave building is a frame construction consisting of horizontal and vertical elements resting on the stone foundation on the ground. Stave churches with elevated naves have a number of staves, or nave posts, which stand separately in the interior and support the upper part of the construction. Heddal in Notodden, Norway, is the largest surviving stave church with elevated naves; it was probably built in the 1200s. Most stave churches were made of Scots pine and oak, which have an extreme density and are hard to find in present-

multistage roofs in Myanmar still show similarities using a series of roofs with wood structures.



1. Trulli of Alberobello, Bari, Italy
2. Beehive Houses of Harran, Turkey
3. Cliff of Bandiagara, Mali
4. Mugsum Mud Huts, Cameroon
5. Stöng Viking Longhouse, Iceland
6. Batak house, Indonesia
7. Stave church, Norway
8. Pyatthat, Myanmar

Figure 2-1. Some vernacular houses in Asia, Africa and Europe (Zune, 2019) and their location's monthly temperature variations (EnergyPlus, 1996, Timeanddate, 1995)

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day Norwegian forests; therefore, the excellent quality timber might be one of the reasons such wooden buildings survived in the Nordic climate for so many centuries.

Typically, additional heating is required for Nordic climates, and additional cooling is required for tropical climates. Therefore, despite similarities of roof design and materials used, many of the passive design techniques found in both types of vernacular architecture to maintain favourable building microclimates for indoor thermal comfort are different. In the Nordic conditions, it is necessary to control heat loss, and this is usually done by using an airtight envelope with a smaller overall window area (Bakken, 2016). In contrast, in the tropics, it is necessary to control solar heat gain so large eave roof shading, and highly permeable building envelopes are observed, besides numerous openings, which are essential to achieve appropriate levels of natural ventilation for passive cooling. The design of stave churches and Myanmar’s traditional buildings with multistage roofs have a parallel development in their historical timelines, even though there appear to be no links between them.

The vernacular architecture reviewed above - although by no means an exhaustive list - show how builders in the past used forms, materials, and ventilation effectively to moderate indoor conditions in their buildings and protect against extreme and prevailing outdoor climatic conditions, and also revealed how the occupants' behavioural, psychological, and social items modified the indoor thermal environments. With this understanding in mind, the thermal comfort quantification for different thermal comfort models was reviewed for different boundary conditions to develop the most appropriate approach to compare and evaluate the results of measured data and simulation studies.

2.2 Thermal comfort quantification

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 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, p34). Skin temperature represents a critical temperature range or threshold (Roaf et al., 2005, p47). Below skin temperature (c.32-35°C), a person can be cooled by convection; above it, they cannot because the ambient air is heating the body, not cooling it. Above this temperature, the body is only cooled by the evaporation of sweat off the skin, which is why hot, dry climates are more comfortable than hot wet ones, because it is easier to lose moisture to the air (and thus cool down) when it is not saturated. 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). There is a scope of subjective and cultural influences in thermal comfort and personal cooling system (PCS) by differences in ethnicity, heat production/metabolism, and long-term thermal history. A study shows that the Asian groups consistently selected a 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).

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). Besides temperature-mortality relation with latitude, 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). Nevertheless, short-term peaks in mortality are associated with heatwaves (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 with 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.

Considering the influences of cultural mechanisms, differences in human interactions with surrounding microclimates and socioeconomic factors, the science of thermal comfort has developed based on a number of subjective perceptions and objective environmental parameters. The context of the thesis was to investigate the building thermal performance through its envelope design quantitively; therefore, the thermal comfort parameters generated by occupants, which could be subjective to the context, were not investigated in this thesis. On the other hand, buildings act as a third skin to protect from outdoor climates, they respond to heat, cold, ground and sky radiation, wind, water vapour, humidity, and other stresses, and the various parts of the building may be considered environmental control devices (Rapoport, 1969).

There are two methods in the judgement of thermal comfort - heat balance and adaptive methods. Buildings are thus designed using either method or both in combination as a mixed-mode or hybrid model. In this case, the benchmarks of building thermal performance and ranges of building thermal comfort are varied by the comfort models; therefore, the following sections presented for these aspects. The remainder of these sub-sections of Section 2.2 provides the background concepts that will be used in Section 2.4.3.

2.2.1 Heat balance model

In steady-state heat transfer calculations, simple boundary conditions are imposed, dynamic aspects of fabric behaviour are ignored (e.g. longwave radiation exchange) (Clarke, 2001, p8), and the temperature is considered as remaining unchangeable during the heat transfer period; therefore, the steady-state regime does not practically occur in a building subject to the weather (Tubelo, 2016, p37-40). It can be assumed that the sum of all heat transfers that occurred through the building envelope is null; this means that the building is in thermal balance (heat balance) (Szokolay, 2008). Fanger (1970) developed the predicted mean vote (PMV) model, which assumes that the human body is in a state of thermal equilibrium with negligible heat storage, and the thermal sensation is predicted based on a function of activity, clothing, and the four classical thermal environmental parameters: air temperature, mean radiant temperature, air velocity, and humidity. At steady-state, the rate of heat production in the body by metabolic activities and the performance of external works equals the heat loss from the body to the environment, by the processes of respiration, evaporation, radiation, convection, and conduction (Haghighat, 2009). The behavioural, attitudinal, or psycho-physiological aspects of human interactions with each other and buildings, and the tendency of people to manage their environments to maintain their personal comfort, are ignored in the heat balance method (Roaf and Nicol, 2017). As a result, in a heat balance model, thermal comfort is achieved if the body temperature can be held in a narrow range; skin moisture is low, and physiological effort of regulation is minimised; the building and equipment size are often designed considering an ultimate acceptable limit (e.g., peak temperature threshold). If the category of the building of buildings is defined by comfort expectation - I for high level, II for normal, and III for a model expectation - the acceptable temperature ranges of predicted mean vote (PMV) for mechanically ventilated buildings in the CIBSE buildings are ±0.2K, ±0.5K and ±0.7K for the category I, II and III buildings, respectively (CIBSE TM52, 2013, p10).

2.2.2 Steady-state calculation in Passivhaus

The Passivhaus standard uses the heat balance method for steady-state calculations in PHPP, where the calculations are carried with a limited range of physical measures relating to space occupied and assumed clothing, occupancy and activity level. The Passivhaus uses pre-heat or pre-cool incoming fresh air to meet the heating or cooling requirements of the super-insulated building; this is an 'active' approach (Hodgson, 2008). Therefore, mechanical ventilation design plays a key role in the Passivhaus design. The frequency of overheating above 25°C should not exceed 10% of the occupied year in a Passivhaus building, which is suggested by the PHI (Feist et al., 2019). Furthermore, a maximum absolute indoor air humidity of 12 g/kg is used as the limit of determining the dehumidification demand in a Passivhaus building. The 25°C limit used in the PHPP is an operational peak air temperature in the heat balance (steady-state) model for thermal comfort. This is aligned with the CIBSE recommendation of 21°C to 25°C for an acceptable summer operative temperature range in dwellings (CIBSE, 2015, p1-10); the CBISE further suggests that the operative temperatures should not exceed 28°C for more than 1% of occupied hours, with some variation for domestic spaces (CIBSE TM52, 2013, p11-12). Note that the definition of operative temperature excludes the influence of humidity. On the other hand, 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, p46). Besides those benchmarks, the best Passivhaus practices suggest keeping this value under 5% of the occupied year due to variation in the prediction of this tool due to the occupant's behaviour in the cold European climates (Mitchell and Natarajan, 2019). Those Passivhaus benchmarks are, in fact, not directly adaptable in the studied country, which has hot and humid climates because the outdoor temperatures are often above 25°C. Therefore, the next sections (Section 2.4.3) discussed the challenges of the Passivhaus concept in the tropics as it is required modifications to reflect the differing comfort expectations of those living in the tropics.

2.2.3 Adaptive model

The heat storage and heat exchange in a building are not at equilibrium; therefore, buildings are not in a steady-state condition practically. Whist the heat balance method discourages natural ventilation, the adaptive method enables it. In the adaptive comfort method, the implications of air movement and humidity are considered, which have particularly significant impacts in hot-humid tropical contexts. For example, people in a humid climate or in conditions when the relative humidity is high, people may require temperatures that are about 1°C lower to remain comfortable, but the main effect of higher humidity is to reduce the width of the comfort zone; in this case, a comfort zone of 2 to 3°C either side of the optimum can be taken as acceptable (Nicol, 2004). In an adaptive thermal comfort model, it is assumed that people tend to adjust their behaviour, clothing and environment in order to make themselves more comfortable. In a free-running mode, a building microclimate changes concerning its outdoor weather, without consuming energy for the purpose either of heating or cooling (CIBSE, 2015); the building is thus naturally ventilated for thermal comfort (ASHRAE, 2013). Many scientific studies have proposed the optimum comfort temperature with regression equations for naturally ventilated buildings as an adaptive model, considering mean outdoor dry bulb temperatures (deDear and Brager, 2002), running mean outdoor air temperatures (Nicol and Humphreys, 2010), or prevailing mean outdoor air temperatures (ASHRAE, 2013). The CIBSE has suggested 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). ASHRAE has suggested that the prevailing mean outdoor temperature should be greater than 10°C and less than 33.5°C (ASHRAE, 2013). The occupants in naturally ventilated buildings are often tolerant of a significantly wide range of temperatures based on a combination of behavioural adjustment and psychological adaptation (deDear and Brager, 1998). Therefore, 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, p10).

2.2.4 The context of the case studies

In both heat-balance and adaptive modes, the comfort temperatures are objectively defined based on collectively considered environmental parameters: air temperature, surrounding surface temperatures, humidity, and airflow rate. Whilst a heat-balance model is designed using a narrow thermal comfort range, an adaptive model is designed for a wide range of temperatures following different passive design approaches such as behavioural adjustments using natural ventilation. Therefore, if a Passivhaus building envelope is used in a naturally ventilated condition of a tropical climate with an adaptive mode, it is important to review acceptable temperature ranges in this mode. In this thesis, the case studies were set to investigate using a naturally ventilated mode, which adopted the adaptive model. In order to offer a more comprehensive picture of user experience in the study climate, the next sections were reviewed to supplement this with the metrics in Sections 2.2.5 and 2.2.6, which offer more detail on the effects of humidity and the collective effects of a wider range of stressors.

Humidity has little effect on feelings of warmth unless the skin is damp with sweat. The physiological results from an environmental chamber for the influence of relative humidity on thermal comfort showed that sufficient evaporation heat losses from the body surfaces are not maintained at higher humidity (Jing et al., 2013). If the influence of humidity on warmth in moderate thermal environments is ignored, humidity in the range of 40–70% RH is generally acceptable (CIBSE, 2015), but thermal discomfort can be happened by high humidity in warm environments. Hence, the effect of humidity is essential to consider for the building thermal performance design in hot and humid climates. For this reason, in this thesis, the wet-bulb temperature and heat-index temperatures were introduced to review; their effect on the indoor thermal environment can then be analysed in case studies.

2.2.5 Wet-bulb temperature

The wet-bulb temperature (WBT) is equal to the DBT at 100% relative humidity; however, the value of WBT is lower than the DBT due to its cooling effect of evaporation. The WBT is widely used in the heat-stress index to assess health risks in physical work situations based on the heat-humidity threshold[31]. Beyond the threshold value of WBT 35°C, which mark our upper physiological limit, any exposure for more than six hours would probably be intolerable even for the fittest of humans, resulting in hyperthermia (Pal and Eltahir, 2016, Raymond et al., 2020). Observed global extreme humid heat shows wet-bulb temperature between 27°C to 31°C for southern Myanmar (Raymond et al., 2020). Therefore, reviewing the impacts of wet-bulb temperatures on building thermal comfort for future climate scenario is an important scope for Myanmar buildings. The study by Sherwood and Huber (2010) reported that human adaptability has a limitation on climate change which is a consequence of heat stress caused by WBT. The WBT equation[32] Eq- (2-1), generated by Stull (2011), as shown below, is presented for wet-bulb temperature as a function of air temperature and relative humidity at standard sea level pressure. By using the equation Eq- (2-1), the WBT can be used to express as an indicator of the temperature for a damp condition which is exposed to the air. As the WBT provides a physically-based relationship to the human body's core temperature based on the heat-humidity threshold, the impact of climate change on the WBT is important to check; for instance, in the current climate, the WBT rarely exceeds 31°C (Pal and Eltahir, 2016).

[31] The wet bulb globe temperature (WBGT) index is the most widely used and accepted index for the assessment of heat stress in industry. It has been published as BS EN ISO 7243, CIBSE TM52 (p.9).

[32] The WBT equation was from an empirical inverse solution which was valid for relative humidity between 5% and 99% and air temperatures between -20°C and 50°C, except for situations having both low humidity and cold temperature. Over the valid range, errors in wet-bulb temperature range from -1° to +0.651°, with mean absolute error of less than 0.3°C.

$$WBT = T \operatorname{atan}[0.151977 (RH + 8.313659)^{1/2}] + \operatorname{atan}(T + RH) - \operatorname{atan}(RH - 1.676331) + 0.00391838 (RH)^{3/2} * \operatorname{atan}(0.023101 RH) - 4.686035 \quad \text{Eq- (2-1)}$$

Where, T = ambient dry bulb temperature (°C)

RH = relative humidity (integer percentage).

2.2.6 Heat index temperature

Heat Index[33] is a measure of how hot it really feels when relative humidity is factored in with the actual air temperature (National Weather Service, 2019, Rothfusz, 1990); therefore, the values depend on the comprehensive contextual climate factors. The degree of heat stress can be calculated by using the heat index equation. A simplified version of the heat index equation is-

$$HI (°F) = -42.379 + 2.04901523\,T + 10.14333127\,R - 0.22475541\,T\,R - 6.83783 \times 10^{-3}\,T^2 - 5.481717 \times 10^{-2}\,R^2 + 1.22874 \times 10^{-3}\,T^2\,R + 8.5282 \times 10^{-4}\,T\,R^2 - 1.99 \times 10^{-6}\,T^2\,R^2 \quad \text{Eq-(2-2)}$$

In Equation Eq-(2-2), T = ambient dry bulb temperature (°F),

R = relative humidity (integer percentage).

$$HI (°C) = -8.78469475556 + 1.61139411\,T + 2.33854883889\,R - 0.14611605\,T\,R - 0.012308094\,T^2 - 0.0164248277778\,R^2 + 0.002211732\,T^2\,R + 0.00072546\,T\,R^2 - 0.000003582\,T^2\,R^2 \quad \text{Eq-(2-3)}$$

In Equation Eq-(2-3), T = ambient dry bulb temperature (°C),

R = relative humidity (integer percentage).

$$\text{Adjustment of HI (°F)} = [(R-85)/10] * [(87-T)/5] \quad \text{Eq-(2-4)}$$

In Equation Eq-*(2-4)*, T = ambient dry bulb temperature (°F), therefore, a unit conversion needs from °C to °F.

R = relative humidity (integer percentage).

[33] The heat index was initially developed in 1978 by George Winterling as the 'humiture' and was adopted by the US's National Weather Service a year later. It is driven from work carried out by Robert G. Steadman. The computation of the heat index is a refinement of a result obtained by multiple regression analysis carried out by Lans P. Rothfusz and described in a 1990 National Weather Service (NWS) Technical Attachment (SR 90-23). The equations use Heat Balance equations, which contains a list of 20 assumption factors as a fixed condition to compute how the factors affect a given situation.

The heat index equation Eq-(2-2) was originally generated using the Fahrenheit scale; therefore, the equation Eq-(2-3) was converted to the Celsius scale. It is important to note that Equations Eq-(2-2) and Eq-(2-3) are obtained by multiple regression analysis and has an error of ± 0.72°C (±1.3°F). If the relative humidity is greater than 85% and the temperature is between 26.67°C (80°F) and 30.56°C (87°F), an adjustment is necessary using Equation Eq-(*2-4*), which was generated using the Fahrenheit scale. Since the body evaporation through the wind passing over perspiring skin (windchill factor) was excluded in the equations, the heat index equations only provide a limited estimate of thermal comfort. Moreover, the Rothfusz regression is not valid for extreme temperature and relative humidity conditions beyond the range of data considered by Steadman (Steadman, 1979), and the regression is not appropriate when the conditions of temperature and humidity warrant a heat index value below about 26.67°C (80°F).

The heat index temperature and its equations were generated from a heat balance condition with a list of 20 fixed assumption factors (Rothfusz, 1990), but was primarily varied by two variables: shade temperature and atmospheric moisture (humidity). The effects of heat index temperatures on occupants can be grouped by temperature and relativity, and their effects on health concern can be defined as four stages: 'caution, extreme caution, danger, and extreme danger'. Figure 2-2 shows the four stages and how a heat index temperature varies according to the related ambient dry bulb temperature and relative humidity.

Despite the limitation of the fixed assumptions, the heat index equation has advantages to check the simultaneous effect of air temperature and humidity, both of which generate either comfort or heat stress. For instance, at the air temperature of 30ºC, if the relative humidity is 80%, the heat index temperature is 38ºC, which is an 'extreme caution' stage. Nevertheless, as airflow rates affect the adaptive thermal comfort of a free-running building, one should not forget that the airflow rate in the heat index equations was a fixed assumption.

NOAA national weather service: heat index

Temperature / Relative humidity	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	86 °F (30 °C)	88 °F (31 °C)	90 °F (32 °C)	92 °F (33 °C)	94 °F (34 °C)	96 °F (36 °C)	98 °F (37 °C)	100 °F (38 °C)	102 °F (39 °C)	104 °F (40 °C)	106 °F (41 °C)	108 °F (42 °C)	110 °F (43 °C)
40%	80 °F (27 °C)	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	94 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	105 °F (41 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	124 °F (51 °C)	130 °F (54 °C)	136 °F (58 °C)
45%	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	87 °F (31 °C)	89 °F (32 °C)	93 °F (34 °C)	96 °F (36 °C)	100 °F (38 °C)	104 °F (40 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	124 °F (51 °C)	130 °F (54 °C)	137 °F (58 °C)	
50%	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	99 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	113 °F (45 °C)	118 °F (48 °C)	124 °F (51 °C)	131 °F (55 °C)	137 °F (58 °C)		
55%	81 °F (27 °C)	84 °F (29 °C)	86 °F (30 °C)	89 °F (32 °C)	93 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	106 °F (41 °C)	112 °F (44 °C)	117 °F (47 °C)	124 °F (51 °C)	130 °F (54 °C)	137 °F (58 °C)			
60%	82 °F (28 °C)	84 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	110 °F (43 °C)	116 °F (47 °C)	123 °F (51 °C)	129 °F (54 °C)	137 °F (58 °C)				
65%	82 °F (28 °C)	85 °F (29 °C)	89 °F (32 °C)	93 °F (34 °C)	98 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	114 °F (46 °C)	121 °F (49 °C)	128 °F (53 °C)	136 °F (58 °C)					
70%	83 °F (28 °C)	86 °F (30 °C)	90 °F (32 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	112 °F (44 °C)	119 °F (48 °C)	126 °F (52 °C)	134 °F (57 °C)						
75%	84 °F (29 °C)	88 °F (31 °C)	92 °F (33 °C)	97 °F (36 °C)	103 °F (39 °C)	109 °F (43 °C)	116 °F (47 °C)	124 °F (51 °C)	132 °F (56 °C)							
80%	84 °F (29 °C)	89 °F (32 °C)	94 °F (34 °C)	100 °F (38 °C)	106 °F (41 °C)	113 °F (45 °C)	121 °F (49 °C)	129 °F (54 °C)								
85%	85 °F (29 °C)	90 °F (32 °C)	96 °F (36 °C)	102 °F (39 °C)	110 °F (43 °C)	117 °F (47 °C)	126 °F (52 °C)	135 °F (57 °C)								
90%	86 °F (30 °C)	91 °F (33 °C)	98 °F (37 °C)	105 °F (41 °C)	113 °F (45 °C)	122 °F (50 °C)	131 °F (55 °C)									
95%	86 °F (30 °C)	93 °F (34 °C)	100 °F (38 °C)	108 °F (42 °C)	117 °F (47 °C)	127 °F (53 °C)										
100%	87 °F (31 °C)	95 °F (35 °C)	103 °F (39 °C)	112 °F (44 °C)	121 °F (49 °C)	132 °F (56 °C)										

Key to colors: Caution · Extreme caution · Danger · Extreme danger

Figure 2-2. NOAA heat index temperature through temperature-humidity scale (National Weather Service, 2019)

2.2.7 A lack of thermal threshold for the Myanmar context

The CIBSE TM55 (2014) highlights that heat stress can occur while the body cannot maintain its core temperature of 37°C. The wet bulb globe temperature index is the most widely used and accepted index for the assessment of heat stress in the industry (CIBSE TM52, 2013, p8). If the influence of humidity on warmth in moderate thermal environments is ignored, humidity in the range of 40–70% RH is generally acceptable (CIBSE, 2007), but thermal discomfort can be happened by high humidity in warm environments. For instance, 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). The impacts of heat-index temperature for heat stress, which is a measure of how hot it really feels when relative humidity is factored in with the actual air temperature, is an alarming concern for the vulnerability of free-running buildings to overheating in tropical countries. Besides the humidity values, the air temperature 37°C limit alone (at which a 'danger' stage heat stress begins with a relative humidity of 40% in shaded areas) is significantly higher than the CIBSE TM52 (2013), and ASHRAE (2013). On the other hand, the thermal neutrality values are different by thermal models (steady-state or adaptive) and psycho-physiological aspects of human interactions with several environmental parameters. For instance, 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. Overheating is often defined by a particular temperature above which a given proportion of people in a building vote on comfort scales; a building is considered overheating above the temperature. The thermal thresholds for building design are crucial for thermal technology (Roaf et al., 2005, p46); however, hitherto, no research and assessments have provided the thermal threshold of free-running buildings for the Myanmar context. Therefore, a review of the comparison method and challenges of the Passivhaus concept in the tropics for thermal thresholds for building design was developed further in Section 2.4 in order to improve thermal performance in Myanmar housing.

2.3 Passivhaus standard

Passivhaus is a building design and delivery concept created by the Passive House Institute (PHI) in Germany that suggests a set of design criteria developed to limit operational energy used whilst achieving maximum thermal comfort (Feist et al., 2019, iPHA, 2016, Passivhaus Trust, 2020). Passivhaus buildings are known for the provision of a high level of occupant comfort while using very little energy for heating and cooling, and can be certified through an exacting quality assurance process (Gonzalo and Valentin, 2014). The concept is based on the idea 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). For warmer climates or seasons, the concept has been adapted to minimise the need for cooling (James and Bill, 2016, Schnieders et al., 2019, Schnieders et al., 2015).

The Passivhaus principles have evolved from many influences, including North American Passive Solar Architecture and Sweden's superinsulated housing (Hopfe and McLeod, 2015, p5). The building envelope of a passive solar house, often found in North America and temperate climates, is designed with properly situated thermal mass to store free solar heat in the daytime for night-time use in winter, with added overhangs and shading to regulate and control solar gain in summer (Chiras, 2002); this is mainly a 'passive' approach. The key difference between a 'passive solar house' and the PHI's 'Passivhaus' is that the latter is designed to pre-heat or pre-cool incoming fresh air to meet the heating or cooling requirements of the building; this is an 'active' approach (Hodgson, 2008). Despite the same goal and similar practices, a passive solar house design solely employs passive design features, whereas Passivhaus relates to well-defined standards and mechanical forms of ventilation and heat control to provide high building thermal comfort with low energy use. Even though a Passivhaus building is not based on a fully passive design approach, the underlying principles of both Passivhaus and passive house are intuitive and highly effective for a low-energy, high thermal comfort, and resilient future.

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). Compact form and optimal use of passive solar gains (e.g. utilising building orientation, glazing ratio, and daylighting) are also suggested as Passivhaus techniques (Hopfe and McLeod, 2015, p7), and these are often found in North American passive solar architecture. According to the PHI, the verification of a Passivhaus design must be carried out using the Passive House Planning Package (PHPP) (Hopfe and McLeod, 2015, p20). In order to access compliance prediction of Passivhaus buildings, the Passive House Institute US (PHIUS[34]) suggested an additional

[34] PHIUS (Passive House Institute US, Inc.) is a non-profit organization committed to making high-performance passive building the mainstream market standard, founded in 2007 by Katrin Klingenberg and Mike Kernagis. PHIUS launched Passive House Alliance US (PHAUS) in 2010 as a non-profit membership-based organization to support the growing network of passive building communities across North America.

two principles for accessing compliance prediction of Passivhaus buildings (Klingenberg et al., 2009, p8): optimized passive-solar and internal heat gains, and modelling energy gains and losses using PHPP.

The compactness ratio has a pronounced influence on the heating and cooling demand, independently of the thermal transmittance value (U-value) of the building fabric (Hopfe and McLeod, 2015, p50). A significant proportion of heat loss in buildings occurs as transmission loss through the envelope, so the higher the proportion of envelope to internal volume, the greater the area for potential transmission heat loss (Lewis, 2014, p30). A built form and its external shape can change energy consumption according to careful configuration and orientation, whereas the building's thermal performance can be independently modified by means of building envelope design. Therefore, the principal Passivhaus certification criteria have vigorously focused on building thermal envelope design.

Despite similar design principles for energy-efficient building envelope design, the European standard and its design parameters for energy comprise one target for heating and cooling to attain an optimized design solution in all climates and cost structures worldwide, while the PHIUS tailors and optimizes energy targets for both climate and cost, and does so for every individual location (PHIUS, 2018, n.d.). Furthermore, a different living space calculation is adopted between the PHIUS and PHI; for example, the PHI calculates Treated Floor Area (TFA) while the PHIUS calculates interior conditioned floor area (iCFA) though each standard excludes interior elements of the building or calculates them as a percentage of the living space (Pierson and Paquin-Béchard, 2017). Differences between PHI and PHIUS do not just exist between the climate zones and area calculation, and there is also no final indication of what a passive house should be like based on the requirements for passive design features, despite the fact that energy use is measurable (Uffelen, 2012, p11).

Although criteria for a passive design feature is not defined specifically, the Passivhaus principles remain the same across the world (Schnieders et al., 2015), so the Passivhaus standard can be adapted to different climates

(James and Bill, 2016), including tropical climates, where MVHR is used without the heat recovery (summer bypass). 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); 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; in this case, shading is a critical passive design feature for Passivhaus buildings in hot and tropical climates. However, 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) (https://passivehouse-database.org). Hence, there is a scope of work to be investigated the synergistic effects between shading, other passive design features and Passivhaus building envelope design for a tropical climate context.

Even highly insulated and airtight Passivhaus buildings with active ventilation can face a summer overheating risk (Mitchell and Natarajan, 2019). Therefore, optimisation of several design inputs for Passivhaus buildings, including external shading devices, thermal mass effect, and glazing ratios, are becoming increasingly relevant to prevent summer overheating even for the temperate climates of the United Kingdom (Abdulla and Rodrigues, 2016, McLeod et al., 2013, Osterreicher and Sattler, 2018, Rodrigues et al., 2016, Rodrigues and Gillott, 2013). Shading offers a microclimate modifier by reducing the outdoor thermal stress and direct solar heat gain. Shading design often concerns aesthetics (Fiorito et al., 2016), building energy conservation (Aflaki et al., 2015), and climate change adaptation (Hooff et al., 2014) for building thermal comfort, particularly for tropical buildings in 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). For the Passivhaus concept to be effective in tropical countries and in future climate change scenarios, there is a need for a detailed investigation of the contribution of passive strategies such as shading to the overall balance, and of the possibilities of relaxing the building envelope parameters in order to suit local contexts (for example, whether the Passivhaus U-values for cold climate is highly necessary for Myanmar). This is a gap in the current literature and therefore the focus of this thesis.

The thermal performance of a building is assessed by the way it is designed - either a heat-balance method or an adaptive method. The Passivhaus is known for its design criteria generated from heat-balance comfort and energy model while ensuring utmost comfort in the interior space within a minimum consumption of resource for operational energy (Gonzalo and Valentin, 2014, Hopfe and McLeod, 2015, Michler, 2015). Despite the fact that the Passivhaus principles remain the same across the world (Schnieders et al., 2015), how a Passivhaus delivers its comfortably energy-efficient design fully relies on the synergistic effects of its criteria and influences by its original philosophy for the European cold climate context. If a Passivhaus is considered a contemporary sustainable archetype, it is worth noting that *“technology is attempting to make location and local culture irrelevant”* (Michler, 2015, p13). Understanding how the Passivhaus criteria have been set for the cold climate is thus essential in reviewing the Passivhaus standard adaptation in tropical climates. Hence, the review of the Passivhaus criteria was firstly discussed in this section.

There is an advantage in learning the real-world Passivhaus studies from the same climates; hence, Passivhaus studies in Brazil, Colombia, Indonesia and Thailand were then reviewed in this section, as the Köppen climate group A is relevant to Myanmar climates. Furthermore, the feasibility study for a Passivhaus in Singapore was reviewed, which helped to develop assumptions in investigating the Passivhaus parameters for the Myanmar climate contexts.

2.3.1 Passivhaus Criteria

Applying these five basic principles, the Passivhaus standard suggests achieving the criteria shown in As discussed before, the Passivhaus overheating benchmark (25°C) is not able to use in a naturally ventilated (adaptive) mode of tropical context directly. Likewise, the minimum acceptable indoor temperature is 22°C is a challenge to use it as a benchmark. Therefore, further study is necessary to review the occupant comfort for a tropical Passivhaus.

Compactness and form factors: In the Passivhaus, the compactness ratio of a building is indicated by the external surface area of the building envelope (SA) to the volume of the building (V) ratio. The 'form factor refers to the building form or shape, measured as a ratio of the external surface area (SA) to the internal usable floor area or Treated Floor Area (TFA). The TFA is the treated floor area, which is the floor area of the rooms within the building that is heated; it excludes the areas of internal partitions, doors, stairs, and unusable spaces. A favourable compactness ratio is considered to be less than 0.7m²/m³, and a heat loss form factor of 3 is tolerable for small domestic dwellings (in a Central European climate); going above these limits may become uneconomical (Hopfe and McLeod, 2015, McLeod et al., 2012).

U-value: The U-value criterion shown in Table 2-3 is required to meet the Passivhaus standard according to the requirements of the Passive House Institute (Gonzalo and Valentin, 2014, p23).

Thermal mass***:*** By default, in the Passive House Planning Package (PHPP), the specific heat capacity as 60 Wh/(m2K) as a minimum value, and an additional 24 Wh/(m2K) is acknowledged for massive envelope areas of a typical room in the building, and an additional 8 Wh/(m2K) for each partly massive envelope area of a typical room (Feist et al., 2019). Thus:

$$c = 60 + ntm\,8 + nm\,24 \qquad \text{Equation 2-5}$$

Where, ntm is the number of partly massive envelope areas
nm is the number of completely massive envelope areas

The total amount of ntm and nm cannot be larger than 6; therefore, for heavy-weight (completely solid) buildings, this results in a thermal capacity of 204 Wh/(m2K). In the cold climate context, thermal mass plays a clear role in reducing the overall duration of overheating in Passivhaus dwellings (McLeod et al., 2013). The PHPP estimates the heat capacity by entering it as an area-specific value with Wh/(m2K); therefore, careful attention needs to be paid to the location of thermal mass. For instance, during the summer, the thermal mass should be shaded from direct sunlight for the entire day, and be exposed to cooling breezes to provide some cooling on hot days and nights. Therefore, more research is needed to investigate the effects of thermal mass in relation to the timing of the dampening effect (decrement delay) during prolonged heatwaves.

Ventilation: The Passivhaus standard posits a clearly defined thermal performance target as a starting point, and suggests using active ventilation approaches to pre-heat or pre-cool incoming fresh air to meet building heating or cooling requirements; this is an 'active' approach (Hodgson, 2008) with a heat-balance method. Regarding natural ventilation, if a window is being used for air change all day long (and not only for night-time cooling), the PHPP suggests a typical temperature difference of 4K between the interior and exterior. During the hot summer period, a wind speed value of 1 m/s is considered for a typical condition with neighbouring buildings, but a wind speed of 2 m/s can be entered for exposed locations. For night-time temperature-driven natural ventilation, the PHPP suggests that the air change rate should be calculated at a temperature difference of 1K, with no wind (Feist et al., 2019). These criteria have been practised in the European cold climate contexts; however, the implications of air movement and humidity have a significant impact in hot-humid tropical contexts if an adaptive comfort model is considered (Nicol, 2004) throughout a year.

Table 2-2. The standard also suggests the following parameters (Feist et al., 2019, Hopfe and McLeod, 2015), which are mainly based on the European cold climate contexts:

- The frequency of overheating above the temperature of 25°C should only be exceeded by less than 10% of the cooling period annually.
- The minimum acceptable indoor temperature is 22°C for additional ventilation regulation.

- Surface temperatures below 13°C indicate the risk of mould and condensation formation.
- Radiant temperature asymmetry should be less than 4.2°K.
- Head to feet temperature difference when sitting (stratification) should be less than 2°K.
- The thermal bridge factor (psi value ψ) should be less than 0.01 W/mK.
- Relative humidity should be between 30% to 70%.
- A maximum absolute indoor air humidity of 12 g/kg can be used as a limit to determine dehumidification demand, and it is suggested that this should not be exceeded above 20% of the year.
- The minimum average air change rate is 0.3 (1/h), for hygienic reasons.
- Airspeed within rooms should be less than 0.08 m/s (<6% dissatisfactory).
- Air supply temperature from heated air should be a maximum of 52°C.
- Air supply to the room after MVHR should be 16.5°C, 10°C lower than the outside temperature.

As discussed before, the Passivhaus overheating benchmark (25°C) is not able to use in a naturally ventilated (adaptive) mode of tropical context directly. Likewise, the minimum acceptable indoor temperature is 22°C is a challenge to use it as a benchmark. Therefore, further study is necessary to review the occupant comfort for a tropical Passivhaus.

Compactness and form factors: In the Passivhaus, the compactness ratio of a building is indicated by the external surface area of the building envelope[35] (SA) to the volume of the building (V) ratio. The 'form factor refers to the building form or shape, measured as a ratio of the external surface area (SA) to the internal usable floor area or Treated Floor Area[36] (TFA). The TFA is the

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[35] This is an external surface area of a building; for instance, 4m length x 4m width x 4 m height a cube shape building has 96 m^2 of external surface area.

[36] The TFA is based on a German standard called WoflV for residential buildings and DIN 277 for nonresidential buildings. In its simplest form it relates to all the useful floor areas within the thermal envelope of the building. The TFA includes some areas at 100% of their area, others at a lesser percentage and some areas cannot be included at all (Ref: Lewis, Sarah (2014)

treated floor area, which is the floor area of the rooms within the building that is heated; it excludes the areas of internal partitions, doors, stairs, and unusable spaces. A favourable compactness ratio is considered to be less than $0.7m^2/m^3$, and a heat loss form factor of 3 is tolerable for small domestic dwellings (in a Central European climate); going above these limits may become uneconomical (Hopfe and McLeod, 2015, McLeod et al., 2012).

U-value: The U-value criterion shown in Table 2-3 is required to meet the Passivhaus standard according to the requirements of the Passive House Institute (Gonzalo and Valentin, 2014, p23).

Thermal mass: By default, in the Passive House Planning Package (PHPP), the specific heat capacity as 60 $Wh/(m^2K)$ as a minimum value, and an additional 24 $Wh/(m^2K)$ is acknowledged for massive envelope areas of a typical room in the building, and an additional 8 $Wh/(m^2K)$ for each partly massive envelope area of a typical room (Feist et al., 2019). Thus:

$$c = 60 + n_{tm}\,8 + n_m\,24 \qquad \text{Equation 2-5}$$

Where, n_{tm} is the number of partly massive envelope areas

n_m is the number of completely massive envelope areas

The total amount of n_{tm} and n_m cannot be larger than 6; therefore, for heavy-weight (completely solid) buildings, this results in a thermal capacity of 204 $Wh/(m^2K)$. In the cold climate context, thermal mass plays a clear role in reducing the overall duration of overheating in Passivhaus dwellings (McLeod et al., 2013). The PHPP estimates the heat capacity by entering it as an area-specific value with $Wh/(m^2K)$; therefore, careful attention needs to be paid to the location of thermal mass. For instance, during the summer, the thermal mass should be shaded from direct sunlight for the entire day, and be exposed to cooling breezes to provide some cooling on hot days and nights. Therefore, more research is needed to investigate the effects of thermal mass in relation to the timing of the dampening effect (decrement delay) during prolonged heatwaves.

PHPP illustrated: A designer's companion to the passive house planning package. Newcastle upon Tyne, RIBA Publishing., p88).

Ventilation: The Passivhaus standard posits a clearly defined thermal performance target as a starting point, and suggests using active ventilation approaches to pre-heat or pre-cool incoming fresh air to meet building heating or cooling requirements; this is an ‘active’ approach (Hodgson, 2008) with a heat-balance method. Regarding natural ventilation, if a window is being used for air change all day long (and not only for night-time cooling), the PHPP suggests a typical temperature difference of 4K between the interior and exterior. During the hot summer period, a wind speed value of 1 m/s is considered for a typical condition with neighbouring buildings, but a wind speed of 2 m/s can be entered for exposed locations. For night-time temperature-driven natural ventilation, the PHPP suggests that the air change rate should be calculated at a temperature difference of 1K, with no wind (Feist et al., 2019). These criteria have been practised in the European cold climate contexts; however, the implications of air movement and humidity have a significant impact in hot-humid tropical contexts if an adaptive comfort model is considered (Nicol, 2004) throughout a year.

Table 2-2. Passivhaus requirements to meet energy demand and building construction

Criterion	Passivhaus requirements
Annual specific space heating demand	≤ 15 kWh / (m^2 a)
or alternative: Heating load	≤ 10 W/m^2
Annual specific space cooling demand	≤ 15 kWh / (m^2 a) + 0.3 W / (m^2a) • DDH
or alternative: Cooling load	≤ 10 W/m^2
AND Cooling demand	≤ 4 kWh / (m^2aK) • υ_e + 2 • 0.3 W / (m^2aK) • DDH – 75 kWh / (m^2aK)
But not larger than	≤ 45 kWh / (m^2a K) + 0.3 W / (m^2aK) • DDH
A primary energy factor (non-renewable primary energy) heating, cooling, ventilation, domestic hot water, auxiliary power, and all other uses of electricity in the building	≤ 120 kWh / (m^2 a) until PHPP v.9.0; ≤ 135 kWh / (m^2 a) in PHPP v9.6 or more
Airtightness (blower door test at 50 Pascals)	≤ 0.6 ach (h^{-1})
Effective heat output capacity of a ventilation unit	≥ 75%
Power efficiency of ventilation unit	≤ 0.45 W / (m^3h)

υ_e: Annual mean outdoor temperature in °C
DDH: Dry degree hours (time integral of the difference between the dew-point temperature and the reference temperature 13°C throughout all periods during which this difference is positive.
h^{-1}: air change per hour (ach)

Table 2-3. Requirements for individual building components to meet the Passivhaus standard

Description	U-value (thermal transmittance value)
Opaque building envelope (roofs, wall, basement ceiling) components with exterior insulation components with interior insulation	$U \leq 0.15$ W/m²K $U \leq 0.35$ W/m²K
Window U-value (installed)	$U_{w,installed} \leq 0.85$ W/m²K
Glazing	U_g – 1.6 W/m²K
External doors (installed)	$U_{d,\ installed} \leq 0.80$ W/m²K

Comfort threshold: Besides the temperature threshold discussed in Section 2.2, the Passivhaus suggests a maximum absolute indoor air humidity of 12 g/kg for a limit of determining the dehumidification demand not to exceed 20% of the year, and the surface temperature to be more than 13°C to use as an indicator for the risk of mould and condensation formation. The tropical climate has an inherent advantage in keeping surface temperatures above 13°C; however, if the Passivhaus' overheating threshold of 25°C is considered for the indoor thermal comfort, a considerable temperature difference between indoor and outdoor temperatures for a tropical climate could be a challenge.

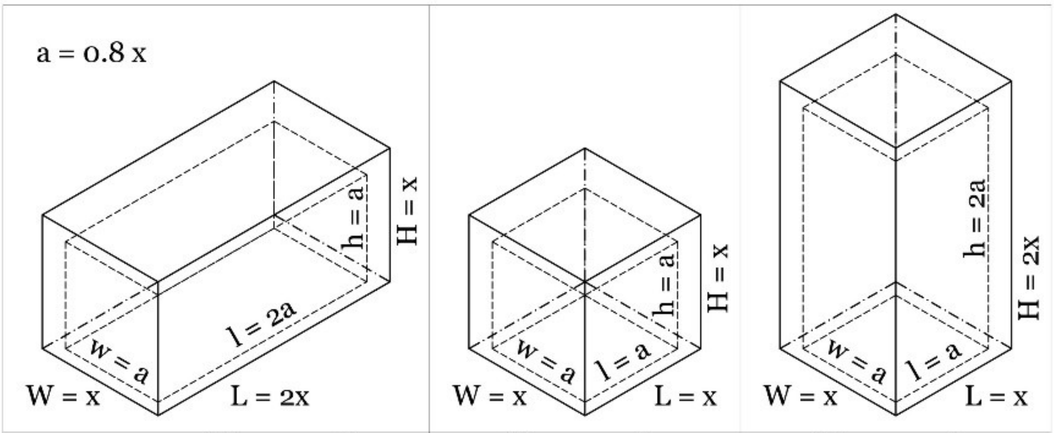
Airtightness and internal gain: Passivhaus suggests a typical infiltration rate of 0.042 ach, based on 0.6 ach @ 50Pa, internal heat gain of 2.1 W/m^2 of treated floor area for single-family homes, 35m^3/h/person as the recommended residential air flow rate, and 30m^2/person for typical residential occupancy (Feist et al., 2019). In practice, the derivation of these figures can be affected by the occupant density, appliances, and services.

Performance certification: The certification requirements of Passivhaus solely rely on the 'comfort criteria' for heath and living comfort, and the 'energy criteria' for energy balance in practice. It is not compulsory to use certified Passivhaus components; however, certified Passivhaus products allow users to verify and compare the relevant parameters of the respective products that support the achievement of an energy-efficient building envelope, substantial durability, and thermally comfortable indoor air quality by omitting the performance gap. For example, super-insulating window frames, thermal bridge-free connection details, and highly efficient ventilation units, etc., are generally about two to four times as efficient as the products commonly used in ordinary construction (PHI, 2020). Therefore, the performance gap, the difference between the thermal performance predicted from building modelling and the actual measured energy in-use once the building is built and occupied (Gupta and Dantsiou, 2013), does not occur with the Passivhaus standard.

Myanmar context: In Myanmar, the length-to-width ratio of a typical timber house is often found as 3:2 or 4:3. For example, a building of 8.23m (27 feet) length has a width of 5.49m (18 feet), as the typical interval span of a timber house is 2.75m (9 feet) due to the limitation of lumber production in Myanmar. This approach not only complements the use of available materials effectively but also leads to achieving a longer span with a narrow width, supporting cross-ventilation; the vernacular Mon house (Chapter-1) is an example. In contrast, the vernacular Bamar house has a separate kitchen with large roof areas for roof ventilation. Furthermore, the Myanmar traditional building with multistage roof shows that the total building height, including the height of the raised floor and the crown of the multistage roofs, varies between 1.25 and 2 times the length or width of the building (Chapter 1).

Figure 2-3 shows the compactness and form factor calculation in Passivhaus. A building with a long span has a smaller form factor; therefore, a terraced house in a cold climate has a smaller heat loss area than a detached house due to its lower proportion of external wall to TFA. Despite the same compactness, a building with a tall building height has a higher form factor due to the smaller TFA; therefore, the tall building with a single zone for internal air volume needs more energy demand for cooling and heating.

The Passivhaus standard considers the form factor as an indication of how much insulation will be required to measure the efficiency of the surface area of the thermal envelope, particularly the calculation is worked it as a heat loss form factor. Therefore, the more compact a building is, the easier it is to be minimised heat loss. Conversely, the less compact a building is, the more insulation will be required for the building be minimised the heat loss. What can be noted from this calculation is that a single zone building with a traditional multistage roof in Myanmar (Chapters 1 and 3) might have a larger form factor, which is a challenge for the Passivhaus approach. In Passivhaus, the effective air volume for ventilation is often calculated with a clear room height of 2.5m (Feist et al., 2019). That could affect Myanmar vernacular practice of stack ventilation through the gable roof.



Compactness,	$\frac{SA}{V} = \frac{5}{x}$	$\frac{SA}{V} = \frac{6}{x}$	$\frac{SA}{V} = \frac{5}{x}$
Form Factor,	$\frac{SA}{TFA} = 7.8125$	$\frac{SA}{TFA} = 9.375$	$\frac{SA}{TFA} = 15.625$

Figure 2-3. Compactness and form factor calculation in Passivhaus

Besides the contrast in built form, the construction method of a highly infiltrated tropical vernacular building envelope is the opposite of the Passivhaus requirements of airtightness. In sum, there are differences in comfort models (heat-balance and adaptive), construction methods and comfort benchmarks between the German Passivhaus standard and Myanmar vernacular practices. Chapters 6 and 7 attempted to explore these aspects.

2.3.2 Passivhaus in Köppen climate group A

This section reviews Passivhaus studies in Brazil, Colombia, Indonesia and Thailand for Koppen climate group A. The Austrian Embassy in Jakarta (ID: 4340 in PHD[37]) is designed and built for a tropical monsoon climate based on the Passivhaus standard. Jakarta, the capital of Indonesia, is located at 6˚S and has a hot and humid year-round climate (Köppen: Am). The wet season in Jakarta covers the majority of the year, running from October through May. The windows in the building are primarily orientated in the north-south direction, which is intended to reduce solar heat gain. Wooden screens for shading and recessing openings obviate direct solar gains in the first place,

[37] Passivhaus Database: https://passivehouse-database.org

and deliver shade. The U-values used in the building are slightly higher than the Passivhaus criteria; the U-values of the exterior wall is 0.32 W/(m^2K), basement floor and floor slab is 0.29 W/(m^2K), the roof is 0.11 W/(m^2K), and the glazing is 1.1 W/(m^2K). In Jakarta, cooling and dehumidification are crucial to removing hot-humid air to achieve thermal comfort. Concrete core temperature control thus delivers cooling by circulating cool water through pipes within the concrete ceilings. The system is associated with coolness recovery ventilation, which covers the cooling load and provides dehumidified air for the indoor thermal comfort for the building (Oettl, 2012, Passive House Database, 2020).

Another Passivhaus study for Jakarta is a terraced house, where rooms were offset from the direct sun using a recessed entrance and veranda. The simulation results, which were validated using field measurements, revealed that the building's predicted air temperatures were affected beneficially by having without the Passivhaus floor insulation, so the ground floor acts as a thermal sink, potentially providing radiant cooling for the building with Passivhaus roofs and walls (Sigalingging et al., 2020).

A detached single-family house (ID: 6340 in PHD) in Bangkok is also designed and built for tropical climate (Köppen: Aw), and located at 13.6˚N. It is the first certified newly built Passivhaus building in Thailand, with the U-values of 0.16 W/(m^2K) for the exterior wall, 0.20 W/(m^2K) for the basement floor and floor slab, 0.20 W/(m^2K) for the roof, and 1.3 W/(m^2K) for the glazing Passive House Database (2020). Furthermore, light colour finishes with the exterior absorptivity value of 0.4 are designed in the Bangkok Passivhaus building to avoid solar heat gain. The reduction factor shading is also designed as 10% for north walls, 35% for west walls, 25% for east walls and 10% for south walls (Yeh, 2020).

For an analysis of typical housing projects in Colombia, Costanzo et al. (2020) used a detached house in Barranquilla and an apartment block in Bogota to assess their thermal and energy performance and to ascertain whether they are suitable for an upgrade to the Passivhaus standard. The capital district Barranquilla is located at 11˚N and has a tropical savanna climate (Köppen:

Aw), so it is hot all year round, with high levels of relative humidity. A high-altitude capital Bogota is located at 4˚N and has a subtropical oceanic climate (Köppen: Cfb). By implementing basic Passivhaus design measures such as improving the thermal resistance of the envelope, providing windows with shading devices, and exploiting night-time ventilation for passive cooling, the simulation results predicted that the Passivhaus standard criteria would be fulfilled in Bogotá, but not in Barranquilla. The outcomes of this simulation study highlight the impacts of the latitude and climate contexts on the same design approach, for which, considerably, greater attention needs to be paid to use Passivhaus building envelope and shading design in the tropical climate context.

The ‘Model House’ is a certified, newly built Passivhaus building (ID: 5892 in PHD) in the Northeast region of Brazil, finished in 2017 according to Passivhaus recommendations (Passive House Database, 2020). The location of the house, São Gonçalo do Amarante, is at 3.6˚S, and has a tropical wet and dry climate (Köppen Aw); the weather there is oppressive and windy all year round. The summers are long, hot, and mostly cloudy; the winters are short, warm, wet, and mostly clear. Besides the external blinds for window shading, the roof of the house is extended for a large eave for roof shading. A note from the Model house is that its exterior wall U-value is 0.21 W/(m^2K), which is slightly higher than the Passivhaus suggested U-values, but less than the U-value of the Austrian Embassy in Jakarta.

The climate of Singapore is hot and humid all year round, which means a tropical rainforest climate with no true distinct seasons (Köppen: Af). Besides differences in their peak intensity and frequency, Myanmar and Singapore have similar tropical climatic parameters; therefore, understanding the Passivhaus standard in the Singapore climate context can help to develop further investigation for the Myanmar context.

Schnieders et al. (2015) presented a hygro-thermal dynamic simulation study for the Singapore climate by using the Passivhaus standard, and the results show that it is possible to realize how the Passivhaus parameters need to be optimized for different climate contexts. The reference building used in

Schnieders et al. (2015)'s study was a terraced house in Hannover that was built to the Passivhaus standard in 1998 Feist et al. (2005). Using the Passivhaus standard, Schnieders et al. (2015) advised that special attention must be paid to humidity aspects in humid climates. That study showed that the indoor peak temperatures were 32°C in the insulated building instead of 37°C for the uninsulated building (Schnieders et al., 2012). However, without active dehumidification, the interior humidity ratio cannot be influenced significantly, even with a well-insulated and airtight building envelope. The study also found that mechanical ventilation and cooling was necessary to maintain adequate thermal comfort throughout the year in the tropical climates; Passipedia (2015) thus suggested considering either the use of an individual split unit air conditioner with dehumidification mode for cooling, or a compact unit for cooling, dehumidification, and domestic hot water for the Singapore context. In that study, there were 38.7 kWh/m^{2}a for cooling demand (26°C @ 60% relative humidity) and 30.7 kWh/m^{2}a for dehumidification demand (70% relative humidity); that was higher than the Passivhaus standard for European climates.

Understandably, the heating and cooling requirements are significantly different between tropical climate and cold climate. Therefore, evidence of the real-world Passivhaus projects and feasibility study in the tropical climate showed that there are several different active and passive design strategies integrated into the tropical Passivhaus design to meet the Passivhaus criteria, in contrast to a Passivhaus building for a cold climate context. Furthermore, they were mostly built with slightly higher U-values than the Passivhaus criteria for cold climates and there were additional design features to meet the local contexts differently (Bere, 2013, Oettl, 2012, Passive House Database, 2020, Yeh, 2020). Therefore, an assumption can be made in this thesis 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; the assumption was used in Chapters 6 and 7.

2.4 Improving thermal performance in Myanmar housing

The tropics are defined as being from the equator to 25° north and south latitudes. This band of the planet is characterised by heavy rainfall, high humidity, and intense solar radiation, but cloudiness causes diffuse solar radiation and lower potential for radiative sky cooling. In the tropics, the minimum average temperature is usually above 18°C, with little daily and seasonal variations (Rosenlund, 2000). In response to these climatic characteristics, the thermal comfort of tropical vernacular architecture is predominantly dependent on a number of passive design techniques, including the choice of building materials, natural ventilation, built form, and shading for passive cooling (Oakley, 1961). Many studies have contributed a great deal to our knowledge of vernacular design techniques in the tropics; however, climatic considerations in vernacular architecture may often be of secondary importance, after behavioural, cultural, and economic influences, in the evolution of the detailed design of these buildings (Meir and Roaf, 2006, p219). Therefore, there is always a need to revisit and investigate the thermal performance of vernacular architecture for their thermal performance in the present and recent climate conditions.

Passive design techniques for building thermal comfort found in Myanmar vernacular houses are presented in Chapter 1. Similar tropical vernacular architecture mechanisms can be seen in Indonesia (Loupis, 1983, Stagno, 2001), Malaysia (Toe and Kubotab, 2015), Thailand (Stagno, 2001, Tantasavasdi et al., 2001), and Vietnam (Nguyen et al., 2011) as well as throughout Southeast Asia and Costa Rica (Stagno, 2001); they share strong similarities and a great variety of passive design. A study of natural ventilation design for Thai houses (Tantasavasdi et al., 2001) found that the climatic condition of Bangkok only provides thermally comfortable indoor environments for 20% of the year, even in suburban areas, and the comfort duration can only be improved by integrating additional passive design techniques; the study was conducted based on 10-year weather database in 2000. Passive design techniques used in vernacular housing in Vietnam enabled thermally acceptable conditions for 58.21% of the year, and 6% of the total time in which indoor air temperature exceeded 31ºC (Nguyen et al., 2011). Likewise, a study of Malay houses found that the periods of indoor operative temperatures exceeded 47% above the ASHRAE's 80% comfortable upper limit, based on adaptive thermal comfort equation (Toe and Kubotab, 2015). Those studies highlighted the shared practices of building thermal performance design in the tropics; it is an adaptive comfort method which has a contrast approach of the Passivhaus standard.

What can be learned from the existing literature is that although "the built form and materiality of vernacular buildings may suggest their climatic provenance, in itself, this is hardly proof of all-year environmental performance" (Weber and Yannas, 2014), and the same inference is true for thermal performance. On the other hand, vernacular buildings ought to be considered as part of a large warehouse of natural and cultural heritage that shows how humans have adapted to extreme conditions over long-term periods (Lawrence, 2006, p111). The vernacular architecture is often linked to 'culture'; therefore, it is essential to clarify qualitatively the ways in which 'culture' and environments are related because the lessons learned from such analysis can be both specific and general (Rapoport, 2006, p183).

Due to global warming, if the increased night-time and mean daily temperatures, extreme heatwave, and changes in humidity are considered, to what extent an adaptive thermal comfort model used in Myanmar housing can provide adequate thermal comfort in the future climate scenario is an open answer depending on the frequency and intensity of overheating conditions. Mechanical ventilation is likely to be a solution to building cooling in summer for the emergence of heat and humidity. Yet building occupant thermal comfort is subjective - the point at which 'acceptable comfort thresholds' will vary from person to person and depend upon a variety of factors. On the other hand, a methodology is required to support design decisions of improving building thermal performance passively without using any active system.

Weather files and occupant behaviour have a significant impact in accessing building thermal performance and overheating of a studied building (CIBSE TM59, 2017). Therefore, it is important to evaluate quantitatively by varying different boundary conditions to understand the relationship between indoor and outdoor thermal environments. For example, it can be investigated how thermal building envelopes (e.g., building insulation, thermal mass, ventilation, etc.) respond to the peak and mean temperatures, heat-stress, and wet-bulb temperature in the present and future climate scenarios. Furthermore, the performances of several passive designs are required to compare and optimise for different boundaries condition. The following scopes were therefore intended to set the scene for how the building thermal performance of Myanmar housing can be improved.

2.4.1 Studied climates

As the climates of Myanmar are varied according to its geography, it is important to select the climate zone and climate scenarios to investigate their effects on Myanmar housing; that will allow selecting building envelope parameters for further investigation. In this thesis, two cities, which represent two Myanmar main climates, were selected for further investigation. Note that Myanmar has three major climates; however, one was excluded in this thesis due to limited research facilities and lack of funding. Furthermore, it is worth noting that CIBSE TM59 (2017) suggests using the design summer years (DSYS) for an analysis of overheating, and it is good practice to take into account future weather files; this consideration was discussed in the future weather file creation in Chapter 3.

2.4.2 Building envelope materials

The building thermal performance of a building is affected by a combination of many complex parameters, including thermal building envelope materials and varied according to and different boundary conditions. The most readily available building materials in the tropics are wood and bamboo, both of which are very strong in tensile strength but poor in thermal mass. However, the use of lightweight timber or bamboo walls complements the outdoor climate in responding more rapidly to changes in indoor air temperatures. A building with raised floors allows increased airflow around and under buildings. Tropical buildings tend to have several openings to provide cross-ventilation. High vents prevent the creation of hot air pockets under the ceiling to remove hot air inside and avoid mould. In addition to the form, the use of roof insulation, large roof eave projection, a ceiling with moderate insulation, and surrounding trees prevents intense solar heat gain (Rosenlund, 2000). Vernacular housing prototypes are considered as inherently adapted to the constraints of the natural environment (Meir and Roaf, 2006, p216). However, tropical vernacular architecture has undergone a radical rethinking of its strategies as a result of post-colonialism and globalization (Lefaivre and Tzonis, 2001). Chapter 1 shows how the housing in Myanmar has come to encompass the use of new materials and construction techniques to reflect socio-economic changes over time, besides issues of tropical climatic elements.

Solar shading is an archetypal building design aspect to optimise solar heat gains (where desired) and visible light while protecting against overheating and glare. Besides comfort needs, shading design is concerned with aesthetics (Fiorito et al., 2016), building energy conservation (Aflaki et al., 2015), and climate change adaptation (Hooff et al., 2014). A variety of fixed and dynamic solar shading techniques have been developed to meet different design and performance requirements, which vary according to building parameters (Eltaweel and Su, 2017), climate elements (Valladares-Rendón et al., 2017), and occupant behaviours (Brien et al., 2013) and preferences. Solar geometry and solar radiation incident have significant impacts on building comfort design; therefore, different shading techniques are found in North America's passive solar houses, tropical vernacular houses, and Passivhaus buildings. Moreover, those buildings have different building envelope designs and ventilation systems. Solar heat gain control and hot-humid air elimination against small diurnal temperature variations are critical in passive design for tropical contexts. Therefore, unlike North American passive solar houses, large eave roof shading and highly permeable building envelopes with numerous openings are observed to be passive design features in tropical vernacular houses (Koenigsberger et al., 1974, Oakley, 1961). If Passivhaus principles are applied in the tropical climate context, which by definition differs from cold climate characteristics, many questions arise concerning the tropical climate elements and building thermal envelope design. Particularly, a combined result of shading design and Passivhaus thermal building envelope properties is still a scope to research for theoretical and practical knowledge to adapt the Passivhaus in the tropical climate context. It is essential to investigate the effect of Passivhaus components and its integrated shading on specific climate contexts using corresponding design tools (Schnieders et al., 2015).

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 either a tropical vernacular lightweight or Passivhaus building envelope, the building is in a purely free-running mode for passive cooling. In this case, the indoor thermal comfort in a building is affected by its passive approach of solar heat gain protection (e.g., shading), its thermal properties of building envelopes, ventilation (also from infiltration), occupants, and other auxiliary loads. Besides that theoretical knowledge, there is still a quantitative assessment of building thermal performance of Myanmar housing for the present and future climate scenarios. No research has discussed how Myanmar's traditional multistage roof response to the indoor thermal performance with lightweight building envelope or whether it is a desirable passive design approach that can be transferred knowledge to improve the thermal performance of Myanmar housing.

For warm, humid climates with little diurnal temperature variation, heat storage has no advantage, and heavy construction will hinder maximum ventilation (Rapoport, 1969, p93); therefore, the use of lightweight building materials for walls and floors is the main principle of tropical vernacular architecture. As daytime temperatures have increased in the tropics and are expected to continue to do so in future climate scenarios, both frequency distributions of temperatures and the length of high-intensity temperature are the foremost climatic parameters in selecting either thermal mass or lightweight building materials. If the longer length of high daytime temperatures in the outdoor climate is similar to the internal environment, due to the results of lightweight construction materials, the traditional naturally ventilated buildings will not be able to perform as assumed. In this case, time becomes an important parameter in defining thermal performance criteria (Forwood, 1995, p178), and the resultant environment will be variable in naturally ventilated tropical buildings.

Unlike a tropical vernacular house, the building envelope of a passive solar house is designed with properly situated thermal mass to store free solar heat in the daytime for night-time use, with added overhangs and shading to regulate and control solar gain. Moreover, insulation for walls, ceilings, floors, foundations, and windows are added, and a passive solar house is sealed to minimize air infiltration but provide adequate air exchange and protect from condensation moisture (Chiras, 2002, Kachadorian, 2006). In contrast, lightweight walls and raised floor can be found in Myanmar vernacular houses, while subject to high infiltration, provide adequate air exchange. If the thermal mass and insulation are applied in the tropics, where high humidity and high temperatures are a norm, radiant temperature, air movement, and moisture content play a major role in determining thermal sensation; a negative result can occur when natural ventilation underperforms. Therefore, if insulation and thermal mass properties are introduced to the Myanmar context following the Passivhaus' fabric-first approach, it is vital to consider the introduced building fabric performance with both active and passive ventilation systems.

A building with high infiltration or ventilation rate delivers building thermal comfort close to the outdoor; the results could vary by time by time. 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 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.

In the PHPP, the room height is suggested as 2.5m by default for a residential building to calculate the ventilated interior air volume; 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. Therefore, 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).

Considering the potential frequency and intensity of overheating conditions based on the given tropical climatic parameters, investigating a broader scope of thermal properties of building envelopes will support the optimisation of building envelope performance design with a more genuine recommendation. In this thesis, as the Passivhaus standard was introduced to the Myanmar context with an aim to improve the building thermal performance of Myanmar housing, two parameters – insulation, and thermal mass – were selected to investigate the selected climates.

2.4.3 Challenges of Passivhaus concept in the tropics

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, p126). A thermal bridge is a localised weak area in the envelope of a building where heat can flow from a warm space to a cold one (Lewis, 2014, p20) because the bridging materials penetrating the thermal envelope have a higher thermal conductivity than the surrounding material (Gorse et al., 2012, p440). A vernacular lightweight wall in the tropic has very small thermal insulation; therefore, thermal bridges are hardly an issue because of the small temperature differences between indoor and outdoor. If a highly insulated Passivhaus thermal envelope with shading is introduced to the tropical context, as direct solar heat gain and indirect heat gains are avoided, thermal bridging is critical because of significant temperature differences between indoor and outdoor. Particularly, if a wall receives direct solar heat gain, a considerable heat flow from outside to inside is expected in a tropic climate. Hence, protecting heat gain (both direct solar heat gain and indirect heat gain) is essential for a tropical Passivhaus building because thermal bridges are dependant in the differences in air temperatures. With this understanding in mind, a shading study for the Passivhaus building envelop was investigated in this thesis and presented in Chapter 6.

A thermal bridge can occur at any junctions where external shadings are mounted to the building envelope, or loggias and balconies connected to walls and floors. It can also occur at any junction where there is a change in the building envelope. Besides the building envelope itself, one of the challenges in using external shading devices in the Passivhaus envelope is the risk of thermal bridge formation. Therefore, loggias at central positions of buildings have the potential for longer thermal bridge length than those at the corner positions, but a building with balconies set in front of the façade has the least potential for longer thermal bridge length (Gonzalo and Valentin, 2014, p35). Unlike a compact built form for a cold climate, building layouts of Myanmar houses, i.e., Bamar house (Chapter 1), tends to have a longer thermal bridge length. Hence, it is challenging in adapting the Passivhaus standard to a Bamar house plan directly.

As mounting external shading devices could have non-trivial effects on the thermal resistance of the walls, Tepfer and Kwok (2013) investigated thermal bridging in external shading devices based on three institutional buildings in Oregon in the US (45˚N), with a dry-summer subtropical climate (Köppen: Csb). Using thermography, heat flux transducers, and thermal two-dimensional heat flow mapping, their measurement, and verification showed that cantilevered steel louvres in Ford Alumni Centre, cantilevered steel frame with steel mesh inset in Lewis Integrative Science Building, and mullionattached, perforated aluminium plates in Allen Hall decreased thermal performance by up to 30% due to the thermal bridge effect. In practical terms, this suggests that if active ventilation is applied in the tropical Passivhaus in Myanmar, thermal bridge-free, airtight envelopes should be designed carefully, as many vernacular Myanmar buildings have been built with highly infiltrated envelopes.

Determining the suitability of insulation material is also dependent on several thermal and physical properties, such as sorption and thermal capacity, gross density, fire performance, water diffusion resistance, solar absorptivity, and emissivity. For instance, the choice of external envelope colour (whether of coatings or materials) can be varied by particular exercises to solve climatic problems. A high-albedo coating roof can offset high temperatures; thus peak power demand (e.g. for cooling during midday) can be reduced (Akbari et al., 1997). An important facet to consider for tropical climates is that mould grows on substrates where the surface relative humidity is at or above 80%. Consequently, it is important to investigate the difference between internal surface temperatures in Passivhaus buildings and the outdoor climate to determine whether surface condensation and consequent mould growth will occur (Hopfe and McLeod, 2015, p61). Such effects also have implications for maintenance, and re-painting and cleaning are frequently required in tropical buildings as a consequence of heavy rain and mould growth; in this regard, particular attention needs to be paid to the selection of external envelope colour and shading types. On the other hand, whether cool roofs, unlike insulation, minimize solar absorption and maximize thermal emission through the exterior surface finish, by increasing the reflectance value (Levinson and Akbari, 2010). In Myanmar, a reflective metal roof is common. As the optimum roof solar reflectance varies under different climate contexts (Piselli et al., 2017), careful consideration is required for a tropical Passivhaus building in selecting solar absorptivity values and thermal insulation. For this concern, roof material study was investigated in this thesis and presented in Chapter 6.

Human changes to the landscape are fundamentally the result of the economic imperative (Sharp, 1940, p20). In Passivhaus, the methodology prizes energy and comfort in an equal measure using high-performance building envelopes to improve thermal comfort, but the economic imperative must always be considered in the built environment. In contrast to the ‘real-world case studies in the UK’ for the economics of Passivhaus construction (Newman, 2015), the cost-effective envelope optimisation for social housing in Brazil’s moderate climates zones, for instance, showed that some high-performance building envelopes would cost nearly 50% more than the traditional envelopes; thus they were deemed unviable, despite their manifest superiority for thermal comfort and sustainability (Tubelo et al., 2018). The Passivhaus Trust UK suggests the Passivhaus quality assurance standard addresses the risks in a number of key stages: procurement process, design, construction, and commissioning (Siddall, 2015). Understandably, a further feasibility study needs to work for the construction cost issue in adapting the Passivhaus building envelope in Myanmar.

2.4.4 Comparison method in this thesis

The usefulness of passive design techniques in vernacular architecture lies in the way they respond to issues in the local context, rather than their product attributes; therefore, identification of general principles and mechanisms are more crucial to understand their important insights rather than basic facts and figures (Asquith and Vellinga, 2006, p14). It is necessary to test what is valuable from the vernacular practices and what is not working in the present climate and local contexts, to develop a model system. Hence, understanding thermal comfort thresholds is crucial to develop a new model system to engage the realities of the present and future climate change scenario.

Regarding the methodology for the assessment of overheating risk in homes, for a free-running mode, CIBSE TM52 (2013)and CIBSE TM59 (2017) suggest that the number of hours during which ΔT[38] is greater than or equal to one degree (K) during the period May to September inclusive shall not be more than 3% of occupied hours in the living rooms, kitchen, and bedrooms. For bedrooms, to guarantee comfort during the sleeping hours, the operative

[38] ΔT the difference between the actual operative temperature in the room at any time and the limiting maximum acceptable temperature.

temperature in the bedroom from 10 pm to 7 am shall not exceed 26°C for more than 1% of annual hours. TM 59 further suggests that the windows in each room should be controlled separately and modelled as open when both the internal dry bulb temperature exceeds 22°C and the room is occupied. For the simulation experiment, TM59 provides the occupancy and equipment gains for different room types. The methodology suggests in TM 59 (CIBSE TM59, 2017) is mainly developed for the temperate climate of the UK; it is challenging to adapt it directly to the tropical climate context. Likewise, as the Passivhaus standard was initially developed using the heat balance method for a cold climate, it is unacceptable if a 25°C limit is used as an overheating threshold for a Passivhaus building with a free-running mode in the tropics. Note that the monthly average outdoor temperature of Darmstadt (Germany), where the world's first Passivhaus building in Darmstadt-Kranichstein was built, is lower than 25°C, whereas the tropical climate of Mandalay (Myanmar) has 67.8% of annual hours above the outdoor dry-bulb temperature of 25°C. When the thermal comfort is switched from the steady-state to free-running mode, a 'jump' in internal temperature, which is an unresolved issue in defining the overheating threshold for a mixed-mode or hybrid buildings.

Due to the limited existing literature for the thermal neutrality value and an overheating threshold for Myanmar subjects, the overheating benchmark 25˚C was used in this study for the steady-state PHPP calculation. The indoor operative temperatures 30˚C, 36˚C and 40˚C were used to check the simulation results generated for scenarios with free-running modes. The values of 30˚C and 36˚C are likely appropriate benchmarks for the context of hot and humid climates; however, note that those values do not represent comfort benchmarks for Myanmar subjects in a free-running mode. Furthermore, the wet-bulb temperatures (Equation 1) and heat-index temperatures (Equations 3 and 4) were reviewed to check the resultant effect of air temperatures and relative humidity.

2.5 Conclusion

In Myanmar, the long-term climate risk index continues to be at high risks (Eckstein et al., 2019, Harmeling et al., 2011), particularly, heat-related mortality and overheating risks in buildings are alarming to investigate the building thermal performance of Myanmar housing for the present and future climate scenarios. However, as mentioned in Chapter 1, no research has found for the building thermal performance of Myanmar buildings in recent years and, therefore, the focus of this thesis.

Chapter 3, which was developed based on simulation experiments using simplified cube-shaped models, presents how the use of vernacular materials, layouts, and building forms can provide thermal comfort in Myanmar housing while identifying challenges in relation to yearly weather and predicted future climate scenarios. Subsequently, using a two-year monitored empirical data sets, Chapters 4 and 5 present the building thermal performance and overheating risks of vernacular and modern Myanmar buildings in order to support other simulation studies validating possibilities in investigating building thermal performance improvement for future climate change scenarios in Myanmar.

Due to the success of Passivhaus principles in reducing building operational energy use and regulating indoor comfort in European climates, the potential implementation of it in other climates has been subjected to much attention in the last few years. However, the requirements of Passivhaus criteria and its application for the tropical climates is a relatively new discussion, especially in Myanmar, where improving building thermal performance for changing climate condition is critical. Whilst the principal Passivhaus certification criteria have vigorously focused on building thermal envelope design, studies have proven that even highly insulated and airtight Passivhaus buildings with active ventilation can face a summer overheating risk.

In this respect, the correct application of thermal mass may represent considerable energy savings and reduce summer overheating risks, for instance, the lightweight construction techniques in UK housing (Rodrigues, 2010). Therefore, optimisation of several design inputs for Passivhaus buildings, including external shading devices, thermal mass effect, and glazing ratios, are becoming increasingly relevant to prevent summer overheating even for the temperate climates of the United Kingdom (Abdulla and

Rodrigues, 2016, McLeod et al., 2013, Osterreicher and Sattler, 2018, Rodrigues et al., 2016, Rodrigues and Gillott, 2013). Shading offers a microclimate modifier by reducing the outdoor thermal stress and direct solar heat gain. Shading design often concerns aesthetics (Fiorito et al., 2016), building energy conservation (Aflaki et al., 2015), and climate change adaptation (Hooff et al., 2014) for building thermal comfort, particularly for tropical buildings in 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). For the Passivhaus concept to be effective in tropical countries and in future climate change scenarios, there is a need for a detailed investigation of the contribution of passive strategies such as shading to the overall balance, and of the possibilities of relaxing the building envelope parameters to suit local contexts. This is a gap in the current literature and therefore the focus of this thesis.

As the combined results of shading design, reducing solar absorptivity and Passivhaus thermal building envelope properties remains a novel area of theoretical and practical research to adapt Passivhaus in the tropical climate contexts. According to the literature review, an assumption can be made that slightly higher U-values for walls and floors, which are more likely to suit the context, can be sufficient in the tropics to achieve Passivhaus targets if the synergistic effects between shading and building envelope design were considered. Therefore, using simplified cube-shaped models, Chapter 6 presents a simulation experiment of Passivhaus building envelope with shading design using the Myanmar climate as a case study.

As a range of research questions, objectives and hypotheses were aimed to test based on simulation experiments with cube-shaped models, finally, there is a question left to be answered, is the Passivhauas' fabric first approach is adaptable in Myanmar housing? Chapter 7 attempted to respond to this query by presenting the comparisons between the results of empirical data sets and simulation experiments of the Passivhaus building envelope study.

Overall, this chapter contributes to – (i) new knowledge and evolution of how the Passivhaus building envelope shows a high level of building thermal performance compared to a typical lightweight, not-insulated building envelope in the Myanmar climates; (ii) understanding of how the building thermal performance of Myanmar buildings can be strengthened and how the earthquake resistance design approach can be integrated by adopting the Passivhaus standard with extensive shading and cool roof, and how the Passivhaus approach can bring both passive technology solutions through building fabric and potential hybrid ventilation (Zune et al., 2018b); (iii) a new knowledge for adopting the Passivhaus fabric-first approach in the tropical climate context, to improve the building thermal performance to cope with climate change impacts on buildings.

Burma is a young nation

judged from modern world standards,

but from a historical viewpoint

the nation has had at least fifteen centuries of

civilisation and culture behind us.

~ U Lu Pe Win,

from Aspect of Burmese Culture, (1957)

[published in the Journal of Burma Research

Society, p19]

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3. Assessing the Effectiveness of Passive Cooling Techniques through Simulations

Climatic considerations in vernacular architecture can often be of secondary importance, after behavioural, economic and cultural influences, in the evolution of detailed design (Meir and Roaf, 2006, p219). In response to climatic characteristics, tropical vernacular housing is predominantly dependent on natural ventilation and passive cooling for thermal comfort (Oakley, 1961). Many studies have contributed a great deal to our knowledge of vernacular design techniques in the tropics and their thermal performance in the present and recent climate conditions (Hindrichs and Daniels, 2007, Koenigsberger et al., 1974, Lefaivre and Tzonis, 2001, Lim, 1987, Mosquera, 2001, Oakley, 1961, Prasetyo et al., 2014, Stagno, 2001). Passive design techniques used in Myanmar vernacular housing, specifically concerning the variation in weather caused by climate change, is still a knowledge gap in the literature and practices. Over the years, Myanmar's vernacular architecture has undergone significant customisation, such as changes in building forms, building plans, building materials and decorative features to meet a wide range of complex needs and social, economic and environmental impacts on building design. Those changes in design have enabled the perpetuity of Myanmar vernacular architecture for many centuries; however, they have also raised the question of whether these buildings still deliver thermal comfort despite the alterations. Hence, there is always a need to revisit and investigate the thermal performance of vernacular architecture for present and future climate contexts; this chapter was attempted to fill this research gap.

In Chapter 1, the passive building design techniques used in Myanmar vernacular house for thermal comfort based on the results of a field visit to the National Races Village were reviewed. The National Races Village showcases replicas of significant symbolic structures characteristic of the major ethnicities residing in the country. A thorough review of the traditional tiered multistage roof design (Pyatthat) was also presented for their stack strategy for thermal comfort using roof ventilation. In this chapter, the first section was structured to investigate how passive design techniques used in Myanmar vernacular houses achieve thermal comfort based on the present and future climate scenarios. The second section was structured to investigate how the changes in roof typologies, roof height, roof ventilation and building materials affect building microclimate for thermal performance of a building with a multistage roof. Although buildings with multistage roofs are not popular in Myanmar housing, the knowledge of passive design techniques in Myanmar vernacular architecture is important to appreciate, as a new insight can be developed for further studies. The methodology for both investigations was presented in the relevant section of this chapter. The simulation case studies aimed to contribute to the knowledge of how the use of vernacular materials, layouts, and building forms can provide thermal comfort in Myanmar housing while identifying challenges in relation to yearly weather and predicted future climate scenarios.

3.1 Vernacular houses

This section presents the investigation of the passive design techniques used to achieve thermal comfort in Bamar and Mon houses. The same houses presented in Chapter 1 [Figure 1-13] were used for the simulation studies. In addition, fifteen types of Myanmar vernacular houses evaluated as listed in Chapter 1 [Table 1-2] was used to investigate how the use of vernacular materials, layout, and building form can provide thermal comfort, while also identifying challenges concerning yearly weather and predicted future climate scenarios in Myanmar.

3.1.1 Methodology

Scope of work: By applying three research stages, the simulation studies aimed to compare the thermal performance of Myanmar housing from various prescribed conditions. The impacts of orientations and window-to-wall ratio on indoor air temperature for a typical model were investigated in the first stage of the study. The impacts of building sizes and floor arrangements on indoor air temperature by comparing two houses were investigated in the second stage of the study. The impacts of various combinations of building components on indoor air temperature by comparing fifteen models were investigated in the second stage of the study. The simulation works were carried out using the *ApacheSim* and *Macroflo* programs, part of the commercially popular and well-known IESVE software (version 2019 Hotfix1). The IESVE is a dynamic simulation software that originated in the UK in the mid-1990s. It is built around an idea of shared content between different simulation tools and qualifies as a dynamic model in the CIBSE system of model classification (IESVE, 2015). *ModelIT* in IESVE is designed to enable appropriate levels of complexity to be incorporated within a model across the entire design spectrum. Shading and solar tracking calculations performed by IESVE's *SunCast*. Apache in IESVE, the thermal analysis programs, calculate heat gains and losses by conduction, infiltration and mechanical ventilation. Long wave radiation exchange is modelled in the Apache using a single radiant temperature for each room. MacroFlo simulates the flow of air through openings in the building envelope and exchanges data with Apache dynamically to achieve the simultaneous solution of the inter-dependent thermal and airflow balances. The calculations are performed for the 24 hours of each design day, on the hour. For simulation results, comfort parameter defaults are set at (CIBSE TM59, 2017) standards in IESVE's *VistaPro*. With its excellent combination of modelling capabilities and the user interface, the IESVE is well-known as one of the industry-standard building simulation tools worldwide (Jankovic, 2017). Many scholars also have used the IESVE with a focus on thermal analysis and shading design (Abu-Hijleh and Jaheen, 2019, Aldossary et al., 2017, Costanzo et al., 2020, McLeod et al., 2013).

Weather files: The simulation studies were compared to the results of the three cities shown in Chapter 1, representing three national climate contexts. The typical weather files used in this thesis were generated by Huang et al. (2014) for ASHRAE. Due to the lack of weather files for future climate scenarios, one future climate weather file for each city was created by adding increased value consistently to the typical 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) and (Cox et al., 2015). Particularly, Cox et al. (2015) examined whether future weather files constructed with coarse temporal resolution data of expected changes in air temperature could provide useful estimates of heating and cooling demand;

their experimental results using both the degree-day method and dynamic simulations indicated the even a single estimate of expected annual change in air temperature could provide very similar estimates of energy consumption to those obtained using fine, hourly temperature change estimates.

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. In order to take into account temperature changes in different seasons, the future weather files used in this thesis were created by adding the predicted absolute monthly mean change value of the dry bulb temperature consistent with the reference weather files. The added values for the future weather files were referred to Chapter 1, Table 1-1, based on the information of the NEX-GDPP dataset (presented in Chapter 1) (Horton et al., 2017, NASA, 2015), where the increased temperatures were 1.4 to 2.9°C for the hot season but 1.1 to 2.4°C for the rainy season. Note that the values were calculated for warming during 2041–2070 based on the baseline model of 1980–2006. The three seasons in Myanmar are affected by the monsoon onset time and withdrawal time; therefore, it is impossible to predict exact weeks and months for monthly mean change value; it was thus assumed that each season has four months. As of November 2020, 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.

Comparison method: The rationale behind the comparison method was initially discussed in Chapter 2. The simulation exercises designed using a free-running mode; therefore, the indoor air temperature (AT) 30°C was used to compare the simulation results, which is a close value of the acceptable internal operative temperature suggested by CIBSE (CIBSE, 2015). For an extremely uncomfortable limit, following the review presented in Chapter 2, the AT 36°C was used in this study to check extreme discomfort in future climate scenarios. Note that the AT 30°C and 36°C were not the benchmark of comfort models and overheating limits for the Myanmar context.

Simulation model: Each building plan and built form have both advantages and disadvantages; therefore, it must determine which configurations have the most pronounced impact on building performance. Using a real-world building as a sample would have been beneficial for decision making, because of its practicality and reality; however, when the time of writing this section, there were no available data sets for thermal comfort study in the Myanmar context; a simplified (surrogate) meta-model was thus used in simulation exercises. 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).

Model assumption and simulation input: For the first stage of the study, a single gable roof model shown in Figure 3-1 was first considered. The model had with 5m length, 5m width, 3m height wall, 2m height roof, and 1m height raised the floor. 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 had the same sizes: 5-metre in length and 5-metre in width.

Firstly, the model with a 20% of window-to-wall ratio (WWR) for four sides of walls was used to test the impact of orientation on the indoor air temperature. Secondly, the same model was used to test the impact of window-to-wall-ratio on the indoor air temperature; however, the window areas varied from 5% to 90% of WWR. All windows were open continuously throughout the year.

For the second stage of the study, the assumption of simulation input data such as the proportion of windows area, window opening time, air infiltration rate, and internal heat gains from occupants and equipment were assigned in the simulation models of the Bamar and Mon houses. The typical models and both houses had a thatched roof, timber floor, timber wall, and timber window.

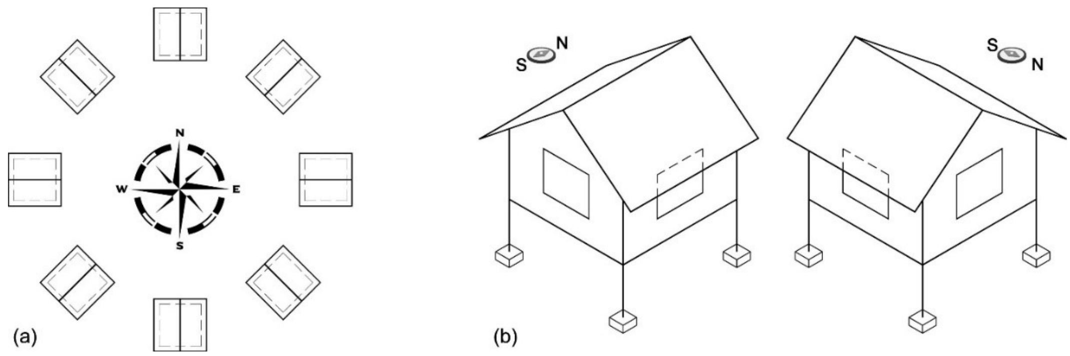

Figure 3-1. (a) Typical model in a plan for orientation studies; (b) Typical model for window-to-wall-ratio simulation with north-south direction gable roof

For the third stage of the study, the fifteen models shown in Figure 3-2 were evaluated based on [Chapter 1, Table 1-2]. The same model sizes used for the first stage of the study were used for the fifteen models. The material properties for all stages of the study were assigned in the simulation models based on the IESVE database (IESVE, 2015) and CIBSE (2015). The data sets for all simulations are shown in Table 3-1 to Table 3-3; the building fabric selection - timber or brick wall, metal roof, concrete floor – were followed the guide, the instruction for masonry house construction in Myanmar (Figure 1-23) (Myanmar Earthquake Committee). In the third stage [Figure 3-2], all windows were open from 06:00 a.m. to 18:00. The ventilation block area in the model H14 was equivalent to the gable vent area. There was a ceiling in the models H3, H6, H9 and H13; therefore, a ceiling void with 0.6m width and 0.6m length was added on the ceiling.

Air infiltration: Jones et al. (1993) estimated the air infiltration rate to be above 30 air changes per hour (ach) in traditional Malay houses, and measured air infiltration of 15 to 35 ach in three modern Malay houses (Jones et al., 1993). As outside air comes into a house through permeable walls, gable vents, floor gaps, and construction joints, all Myanmar vernacular houses can be presumed to have similarly high air infiltration rates. The air infiltration and air leakage rate are affected by an area of a leak and the pressure behind it. Therefore, it is important to understand that the airtightness requirements should be based on surface permeability – walls, floor, and ceiling area, although the number of times the volume of air within the building is changed in an hour is often a volumetric measure of the air change rate (ach). However, due to the lack of measured data and literature for Myanmar housing, the air infiltration rate 15 ach was therefore assumed for the timber models H1 to H9, which was 10 times higher than the rough assumption 1.5 ach for the brick models H10 to H15.

Table 3-1. The proportion of windows areas in the Bamar house and the Mon house

	Window area (Approximate widow area for total floor area)	
	Bamar House	Mon House
West	11.1	2.8
North	8.3	*7.3
East	7.2	5.7
South	5.4	5.3
Total	31.9 (51.5% of total floor area)	21.1 (29.61% of total floor area)

*Note: Area of veranda opening was excluded.

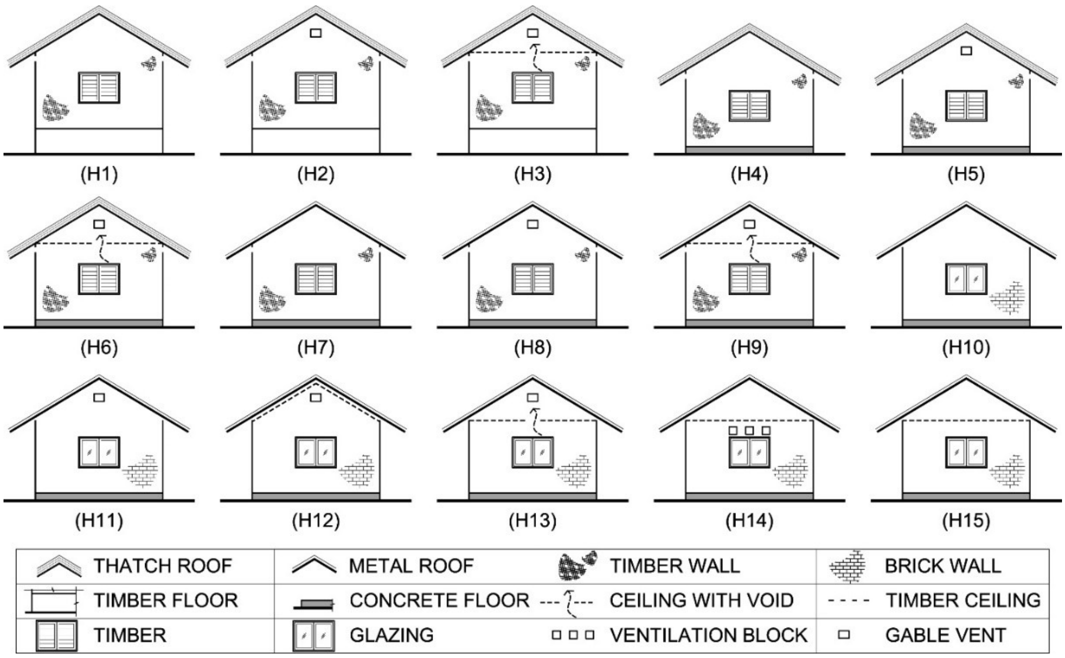

Figure 3-2. Model of fifteen scenarios in the study and their material use

Table 3-2. List of components used in the simulations, dataset based on (CIBSE, 2015, IESVE, 2015)

	T	λ	D	Cp	U	Cm	SA
Thatch roof	300	0.07	240	180	0.29	4.3	0.7
Metal roof	15	0.19	960	837	2.67	5.5	0.3
Timber floor	25	0.14	650	1200	2.70	9.8	0.5
Concrete floor	500	-	-	-	0.79	174.7	-
Screed	-	0.41	1300	1000	-	-	-
Sand	-	0.35	2080	840	-	-	-
Timber wall	25	0.13	900	2000	2.92	22.5	0.5
Brick wall	250	-	-	-	1.67	124.6	0.5
Plaster	-	0.16	600	1000	-	-	-
Brick	-	0.84	1700	800	-	-	-
Timber ceiling	25	0.17	650	1600	2.73	13.0	-
Timber window / door	40	0.13	900	2000	2.19	36.0	-
Glazing	12	-	-	-	5.75	-	-

T = Total thickness [mm]; λ = Conductivity [W/(mK)]; D = Density [kg/m^3]
Cp = Specific heat capacity [J/(kg.K)]; U = Thermal transmittance [W/m^{2}K]
Cm = Thermal mass [kJ/(m^{2}K)]; SA = Outside surface Solar absorptance

Table 3-3. Simulation input data in the Bamar and Mon house

	Assumption	Properties	Operation
1.	Occupants (two persons)	Maximum sensible gain 60 W/p; Maximum latent gain 40 W/p	All the time
2.	Fluorescent lighting and other equipment	Maximum sensible gain 120 Watts	06:00 to 09:00 and 16:00 to 22:00
3.	Window opening	-	06:00 to 18:00
4.	Air infiltration rate	15 ach and 1.5 ach	All the time

3.1.2 Simulation results

The results of IESVE simulations were presented on an annual basis. Note that the percentage of a year in the results was defined as the percentage of the annual hours of a year, which is 8760 hours for 100%.

Impacts of orientation, window-to-wall ratio, and infiltration: According to the weather outdoor, there were 17.8%, 28.4% and 12.6% of annual hours above dry-bulb temperature 30°C in Yangon, Mandalay and Myitkyina, respective. As shown in Figure 3-3, besides additional heat gains through ventilation and internal gain, it was found that there were insignificant differences in AT between the four cardinal and four inter-cardinal directions. That could be due to high diffuse radiation throughout the year (Figure 1-8). The comparison of WWR revealed that the larger the WWR, the lower the percentage of the annual hours above AT 30°C; however, when the window was continuously open, the percentage of the annual hours were reduced by up to 5% by changing WWR from 5% to 90%, due to high ventilation exchange from the larger window area. As the indoor air temperature can be influenced by ventilation heat gain from window opening and the air infiltration rate, in addition to the initial infiltration of 15 ach for timber, when the infiltration rate was tested by increasing from 0.3 ach to 3.0 ach, the overheating duration was decreased, that showed allowing high infiltration could promote higher thermal comfort in the studied climates.

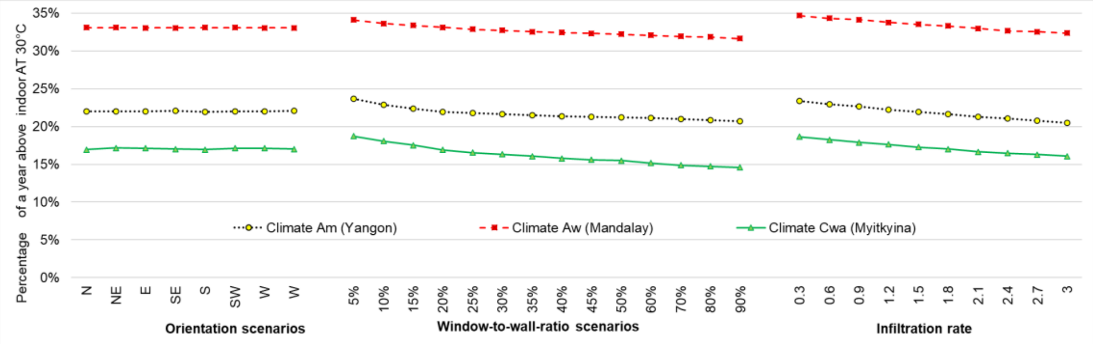

Figure 3-3. Impacts of orientation, window-to-wall ratio and air infiltration rate in three cities

Impacts of building size and plan: The results shown in Figure 3-4 indicate that there were small differences between the two houses regardless of building size and floor plan arrangement differences. In the Bamar house, the kitchen received a lower percentage of the annual hours above AT 30°C than the bedroom for the parent. In the Mon house, the veranda received a lower percentage of the annual hours above AT 30°C than the bedroom for a daughter; the differences between the two rooms were 4.53%, 4.78%, and 4.38% in Yangon, Mandalay, and Myitkyina, respectively.

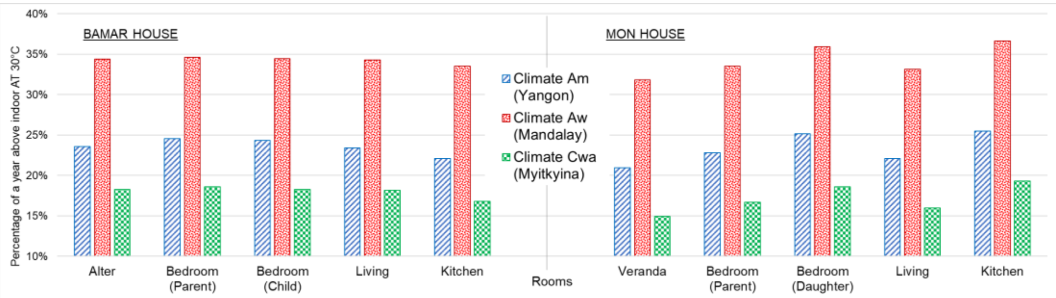

Figure 3-4. Comparison of Mon and Bamar houses, typical weather years in three cities

Impacts of ventilation techniques and building materials: The results of indoor air temperature ranges for the fifteen models for typical weather years of three cities are shown in Figure 3-5. For the timber models H1 to H9, the worst result was found in the model H7. For the brick models H10 to H15, the worst result was found in the model H10. In Yangon and Mandalay, more than 50% of the annual hours were above AT 28ºC in models H10 to H15, while the timber models H1 to H9 maintained 60% of the annual hours below AT 28ºC. The percentage of the annual hours above 36°C showed the risks of heat stress in all free-running models. Similar monthly temperature variation profiles were found in all scenarios; Figure 3-6 presents the results of the models H1, H7, H10, and H15 for a typical weather year in Yangon. The highest peak temperature in April was decreased in the model H15 compared to the model H7; the model H7 had timber walls and no ceiling; the model H15 had brick walls and ceiling. Model H1 received the lowest peak temperature 14.15ºC in December, and values of 14.46ºC, 16.73ºC, and 17.72ºC were recorded for models H7, H10, and H15, respectively.

The simulation results of typical weather year and future climate scenarios for three cities are compared in Figure 3-7. When the roofs were changed from thatched roofs to metal roofs, the indoor temperatures were significantly increased, as shown in models H6 and H7. The thatch roof had a high degree of insulation with a lower U-value than the metal roof, which had no insulation. The boundary layer heat transfer fundamentally occurs by three agencies: free convection, forced convection, and radiation (Diamant, 1965, p29). Adding insulation layers in building envelopes mainly addresses the first two agencies while a reflective metal roof addresses the last agencies. However, the solar absorptivity values were set as 0.55 in this study, which had some degree of absorptivity with less reflective values. Therefore, it was found that the thatched roof model H4 performed better than the metal roof model H7. The timber wall model in H7 and the brick wall model in H10 had the same metal roof but no gable vent; however, both models received a higher percentage of the annual hours above AT 36°C than the other models. There were minimal differences between the metal roof models H7 and H8, although the gable vent was added in the model H8; the indoor temperature of the model H9 was dropped when the ceiling was added to it. Obvious results of the ceiling and roof ventilation can be found by comparing the models H10 and H13; however, there were small differences between the models H1 to H3. A better performance was found when the gable vents and ceilings were added in the models H12 to H15. The model with the false ceiling (H13) performed better than the model with a ceiling under the gable roof (H12). Although the ventilation blocks were replaced with the gable vent, there were small differences between the models H13 and H14. Nevertheless, the percentage of the annual hours above 36°C was significantly increased in all models in the future climate scenario. In all simulations, the worst results were found in the models located in the equatorial winter dry climate zone, which was Mandalay.

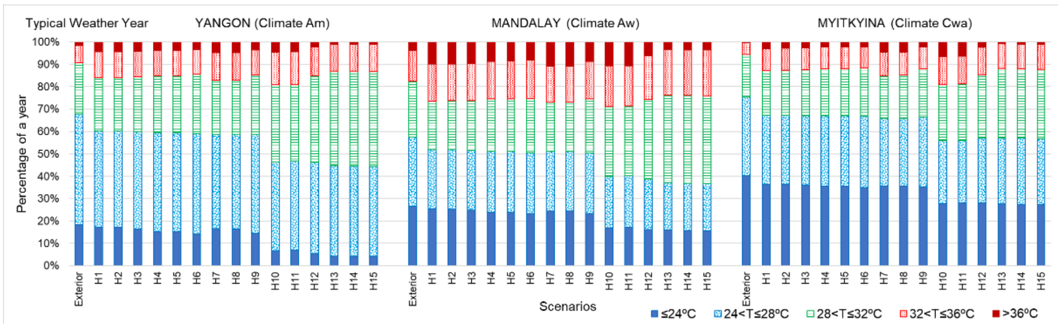

Figure 3-5. Indoor temperature range for fifteen models, a typical weather year

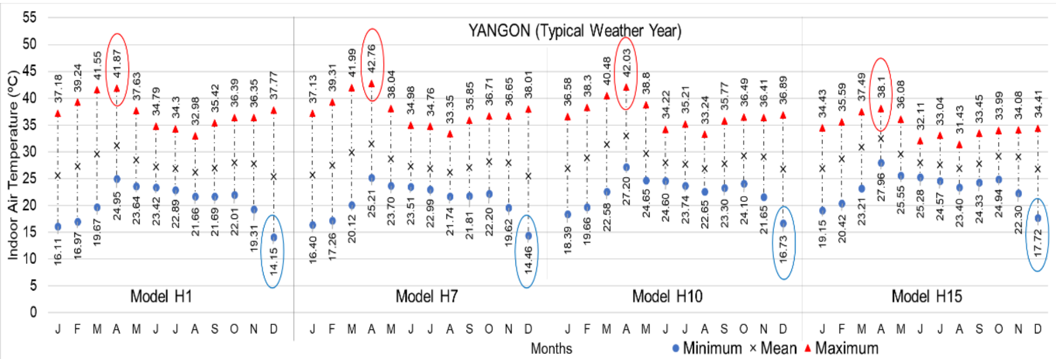

Figure 3-6. Monthly temperature variation in model H1, H7, H10 and H15 in Yangon

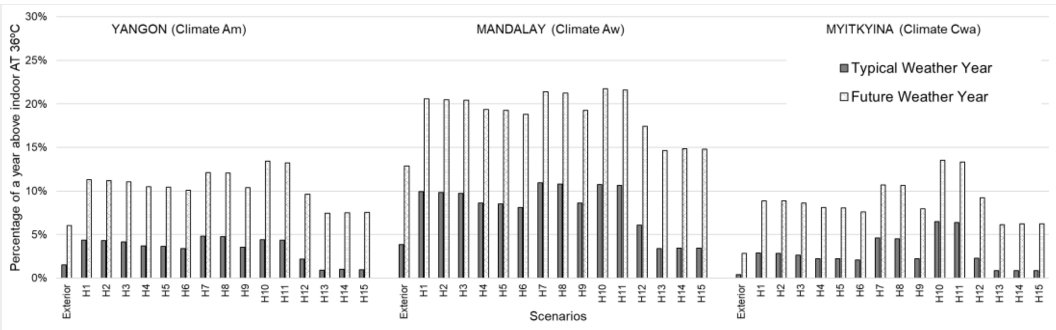

Figure 3-7. Comparison of a typical weather year and future climate year for fifteen models

3.1.3 Discussion

In the first stage, there were negligible differences between the eight orientations in terms of the indoor air temperature in the small-scale model. These results were in agreement with the study conducted by Morrissey et al. (2011); their ANOVA tests showed that smaller houses had significantly smaller ranges of energy efficiency ratings across eight orientations, in comparison to larger houses (Morrissey et al., 2011). However, it needs to be acknowledged that the results could rely on several parameters such as its exposed surface area to volume ratio, air infiltration and diffuse solar radiation.

The simulation results of this study showed that a model with a large window-to-wall ratio had a better result than others. Regarding the use of natural ventilation, there are five constraints: it does not work in the hot air condition; high natural ventilation is necessary for the warm air condition; moderate ventilation is appropriate in the comfortable air-condition; natural ventilation is not appropriate in the humid air condition; and minimal ventilation will help in the cool and humid air condition (Tantasavasdi et al., 2001). When high humid air holds a higher temperature for a long time, a complex outcome of combining high humidity and high air temperature in the tropics causes the increase of warm air inside the space; therefore, higher ventilation both from a window and air infiltration is often found as a vernacular passive design practice for a lightweight building to remove the warm air inside. Therefore, it can be suggested that if the external temperatures are too high, if a lightweight envelope with natural ventilation alone - which is often closely reflected by the weather outdoor - is not able to provide adequate thermal comfort, mechanical ventilation is an option. If mechanical ventilation is introduced, highly infiltrated vernacular enveloped is required to modify. Overall, the first stage of the study provided fundamental knowledge about the relationship between the Myanmar climates and the test models.

In the second stage of the study, difficulties were describing the precise role and importance of building design features from two houses, as their simulation results were very similar. On the other hand, notably, the impact of the exterior climate was more significant than the described building layouts.

In the third stage of the study, it was found that there were substantial effects of roof insulation and roof ventilation on indoor air temperature. The traditional techniques presented in the models H1 to H3 closely experienced the exterior weather. On the contrary, the modern custom presented in the models H12 to H15 had a better thermal performance than others to prevent the peak temperature; however, increments in annual mean temperature were not addressed in those models. On the other hand, the results of the fifteen models were in agreement with the study conducted by Samuel et al. (2017); their case study in India also showed that passive architectural features in a traditional building could provide thermal comfort if employed correctly, using materials such as bricks and metal for walls and roofs (Samuel et al., 2017).

3.1.4 Findings

The section presents the vernacular passive design techniques in Myanmar housing with a focus on their thermal performance. It was compared to the impacts of three climate contexts and passive design techniques on indoor thermal environments of Myanmar housing by using air temperature alone, with 30°C and 36°C as thresholds. Further studies are necessary to address the importance of thermal thresholds (Roaf et al., 2005) concerning the climate and people of Myanmar. Future weather files used in this study were further limited because some parameters such as solar radiation, sky cover, relative humidity, wind, and precipitation were not changed in the future weather files as they were duplicated from the typical weather files. However, at the time of writing this study in 2017, there were no data sets available for Myanmar climates, even in CCWorldWeatherGen or Meteonorm. As of November 2020, the Meteonorm data sets for Myanmar come without global radiation. In order to fill this gap and limitations, the studies of heat-index analysis for Myanmar climates were presented in Chapters 4 and 5. Although the confidence of simulation studies was influenced by the accuracy of weather files, the studies provided a comprehensive body of knowledge about Myanmar vernacular housing from vernacular designs to modern customs for three Myanmar climate zones.

It was found that the indoor thermal environment of the models with vernacular lightweight walls and thatch roof was closely experienced the weather outdoor. Furthermore, it was found that using a gable vent for stack ventilation or adding ceilings helped to reduce the peak temperatures. Therefore, the next section was structured to investigate the impacts of roof ventilation using Myanmar traditional multistage roofs.

The simulation results revealed that natural ventilation and roof shading in Myanmar vernacular architecture might have been an optimal thermal comfort performance in the past; however, the increasing outdoor temperatures and changes in rainfall caused by global warming and climate change are threatening the thermal performance of Myanmar housing. Considering the classic challenges of tropical climatic characteristics in Myanmar housing and the climate change crisis, there are demands for improvements in Myanmar housing to achieve adequate thermal performance.

According to the results obtained in this study, vernacular houses in Myanmar might face challenges in indoor thermal comfort; therefore, this study suggests that new climate adaptation strategies are necessary for Myanmar housing for different climate zones. As one of the biggest challenges for Myanmar is the climate change risk, a concluding question of this study is how Myanmar housing can improve thermal performance. Further studies need to include empirical and quantitative assessments of building thermal performance data sets and qualitative assessments of occupant comfort to generate more specific scientific information for sustainable climate adaptation strategies in Myanmar housing.

3.2 Traditional buildings with multistage roofs

The study of Myanmar vernacular houses (Section 3.1) reveals that the efficacy of traditional passive design techniques used in the Myanmar vernacular houses would not be sufficient to achieve thermal comfort in the present and predicted future climate scenarios. Myanmar traditional buildings with multistage roofs represent not only the unique culture of Myanmar but also similar passive design techniques for building thermal performance in different building scales. Therefore, it is important to investigate the use of multistage roofs in Myanmar's traditional buildings in terms of their thermal comfort performance using stack strategy to identify whether they are inherently vulnerable to overheating risks due to the pervasive threat of the climate crisis. Hence, this section presents the impact of multistage roofs on the performance of Myanmar's traditional buildings. Various building parameters, including form and materials, were investigated using dynamic whole-building simulation and computer fluid dynamics (CFD) to identify whether they are inherently vulnerable to overheating risks due to the pervasive threat of the climate crisis. Figure 3-8 presents the research method deployed in this study. This work contributes to the ongoing resilience of Myanmar vernacular architecture.

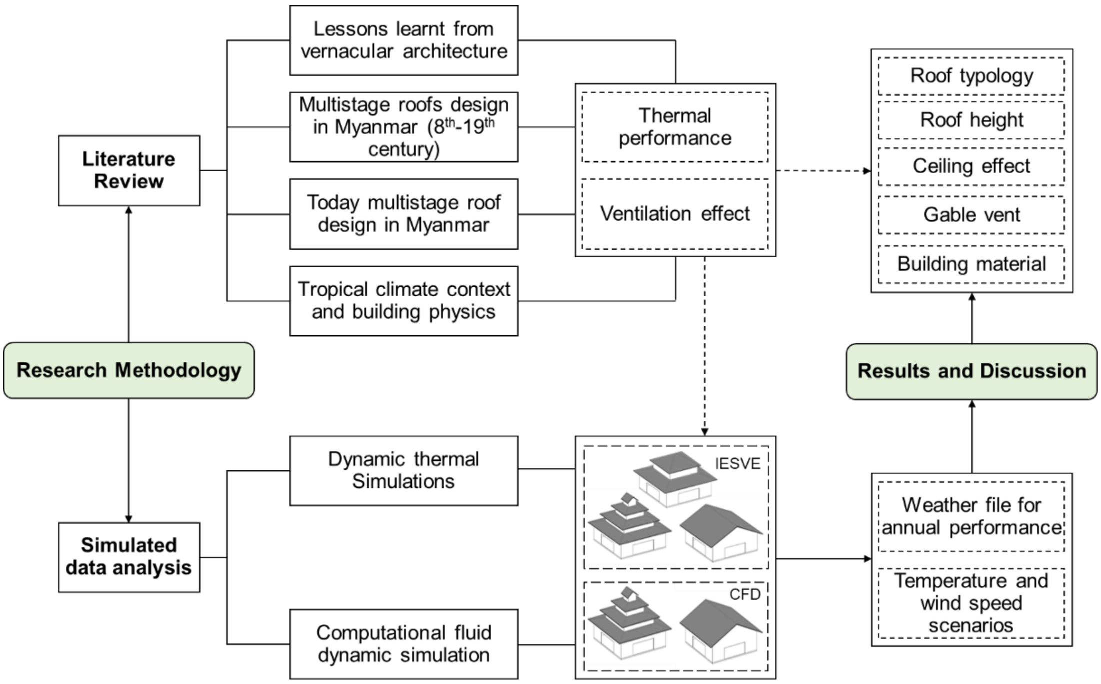

Figure 3-8. Research approaches and steps proposed and applied in this study

3.2.1 Methodology

In order to evaluate the contribution of each roof typology, roof height, roof ventilation and building materials on the thermal performance of a building with a multistage roof, the following key questions were set:

1. How does varying the building envelope materials affect the thermal performance of the different roof typologies?
2. Which roof typology is more effective in reducing the indoor air temperature? Which roof typology has the most effective indoor airflow?
3. To what extent can the building with multistage roofs improve the indoor thermal environment?

The simulation buildings were modelled with a single zone using dynamic thermal simulation and computational fluid dynamics simulation (CFD) programmes. The dynamic thermal simulations focused on investigating the resultant overall indoor air temperatures of three building typologies [Figure 3-9] with various conditions. The CFD simulations focused on investigating the air temperatures and airflows of two building typologies [Figure 3-10]. Each program has a different capability to calculate building thermal performance results; for example, the IESVE generates hourly-based time series results, and the CFD solves issues of fluid flow such as velocity and density; therefore, the results from both programs cannot be justified directly.

3.2.1.1 Dynamic thermal simulation

Simulation engine: The simulations were performed using the Integrated Environmental Solution software (version 2019 Hotfix1), which was also used in Section 3.1.

Building geometry: A building with a three-stage hipped roof (3R), a building with a one-stage hipped roof (1R) and a building with a single gable roof (0R) were used in the dynamic thermal simulation. Regarding the geometries of the buildings [Figure 3-9], the sizes of the occupied space were first fixed as 18m in length, 18m in width, and 5m in height. The full height of the building was set as 15.15m based on building 3R; therefore, the total height of buildings 1R and 0R were lower than building 3R. The size of the intermediate roof structures was increased in building 1R to retain the same internal air volume. The characteristics of the building geometries and building abbreviations, as shown in Figure 3-9 and Table 3.4, mean that the internal air volumes of each building were fixed, but the heights of the three buildings were different. Regarding the abbreviations that describe the models, the suffix 'n' represents the buildings with no gable vents in the roof structures and the suffix 'v' represents the buildings with gable vents in the roof structures.

Opening: In the occupied spaces of all buildings, a total of 108 m^2 (equivalent to 30% of the window-to-wall-area-ratio of the occupied space) for the fenestration areas was equally distributed across all four sides of the walls. Additionally, the gable vent area 23.92 m^2 was equally split into all the roof stages of the buildings 3Rv, 1Rv and 0Rv. Geometrically, there were 12 scenarios – three roof typologies, two ventilation modes, and two ceiling modes - shown in Figure 3-9. The ceiling modes were the buildings with ‘no ceiling’ and the buildings ‘with ceilings’ added. For the latter mode, a 600 x 600 mm size ceiling void at every 6m intervals was added in each building to remove the air through the gable vents. Regarding the opening time for fenestration, the fenestration of occupied space from all buildings was opened from 06:00 a.m. to 6:00 p.m., which means they were opened during the daytime. The gable vents in the roof spaces were continuously open.

Internal gains: In order to simplify the effects of internal gains in the CFD simulations, the dynamic thermal simulations for all buildings were generated with no internal gains from the occupants, equipment or lighting. Myanmar’s vernacular buildings are a free-running building type; therefore, both simulations were generated by using natural ventilation mode.

Materials and simulation scenarios: The 12 scenarios doubled when two sets of building materials were considered for the building envelopes, as shown in Table 3-5. Therefore, there were a total of 24 scenarios due to variations in typologies, ceiling modes, building materials, and ventilation modes. The material set-1 contained thatch roofs, timber floors, timber walls, timber ceilings, and timber windows. The material set-2 contained metal roofs, concrete floors, brick walls, timber ceiling, and glazed windows. Note that the buildings shown in Figure 3-9 and Table 3.4 are those with material set-2.

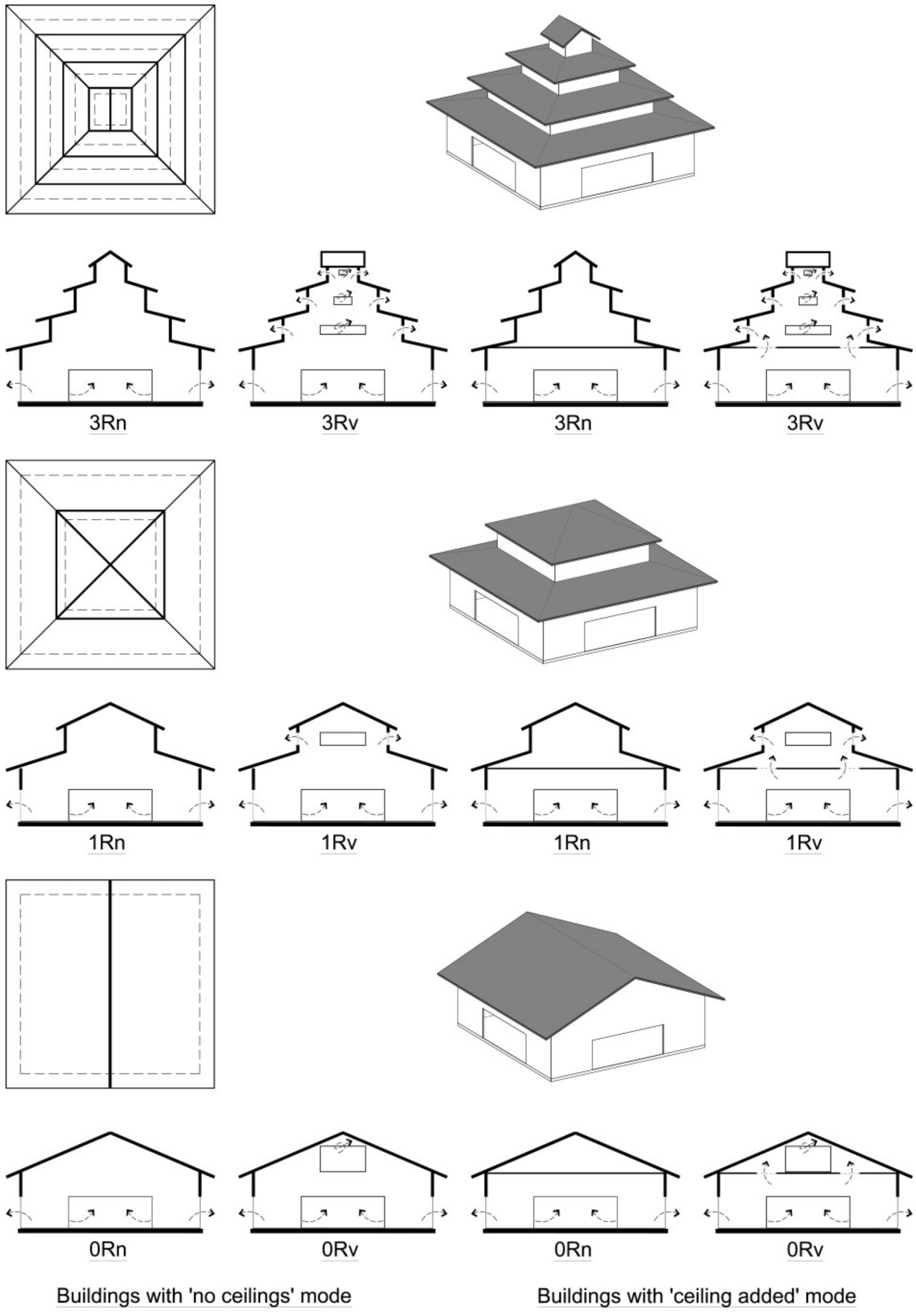

Figure 3-9. Twelve building typologies used in the dynamic thermal simulations; material set 2.

Therefore, the total building height for each building of the material set-1 will be 3m higher than the material set-2 because of the raised floor height for a timber floor. The infiltration was set as 10 ach for the buildings with material set-1 and 1.5 ach for the buildings with material set-2, which were rough assumptions from a similar vernacular house (field measurement data sets of a traditional Malay village house) (Jones et al., 1993). The results of dynamic thermal simulations were compared with the results of computational fluid dynamics simulations.

Weather file: Most of the surviving buildings with multistage roofs can be found in Mandalay (21°58′N 96°5′E), the last royal capital of Myanmar, located in the central dry zone of the country. Therefore, the Mandalay typical weather file for dynamic thermal simulations was chosen to use. Long-term historical weather data and future climate data are generally unavailable or very limited in Myanmar. The same typical weather file used in Section 3.1 was used in this study.

Table 3-4. Geometry characteristics of the buildings used in both simulations

Buildings	Gable Vents contained	Building Height	Window Areas (m^2)	Gable Vents Areas (m^2)	Room air volume (m^3)
3Rv	Yes	15.2	108	23.9	2450
3Rn	No	15.3	108	0.0	2450
1Rv	Yes	11.9	108	23.9	2450
1Rn	No	11.9	108	0.0	2450
0Rv	Yes	9.5	108	23.9	2450
0Rn	No	9.5	108	0.0	2450

Table 3-5. Material properties used in the IESVE simulations (CIBSE, 2015, IESVE, 2015)

	T	λ	D	Cp	U	Cm	SA
Material Set 1							
Thatch roof	300	0.07	240	180	0.22	7.7	0.7
Timber floor	25	0.13	900	2000	2.92	22.5	-
Timber wall	25	0.13	900	2000	2.92	22.5	0.5
Timber ceiling	25	0.16	650	1600	2.73	13.0	-
Timber window	40	0.13	900	2000	2.19	36.0	-
Material Set 2							
Metal roof	15	0.19	960	837	2.37	27.5	0.3
Concrete floor	500	-	-	-	0.80	174.7	-
Screed		0.41	1200	840			
Sand		0.35	2080	840			
Brick wall	250	-	-	-	1.67	124.6	0.5
Plaster	-	0.16	600	1000			
Brick	-	0.84	1700	800			
Timber ceiling	25	0.16	650	1600	2.73	13.0	-
Glazed window	12	-	-	-	5.75	-	-

T = Total thickness [mm]; λ = Conductivity [W/(mK)]; D = Density [kg/m^3]
Cp = Specific heat capacity [J/(kg.K)]; U = Thermal transmittance [W/m^2K]
Cm = Thermal mass [kJ/(m^2K)]; SA = Outside surface Solar absorptance

3.2.1.2 Computational fluid dynamics simulations

Numerical modelling method: The numerical simulations were carried out using ANSYS FLUENT 18.1 software. The assumptions for the steady-state simulation comprised a three-dimensional, fully turbulent and incompressible flow. The turbulent nature of the flow was modelled by the standard K-epsilon turbulence model (k–ε), which is well established in the field of natural ventilation and windcatcher research (Calautit and Hughes, 2016, Calautit et al., 2015). The CFD code used the Finite Volume Method (FVM) approach and employed the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) velocity-pressure coupling algorithm with the second-order upwind discretisation.

CFD theory: The governing equations for the 1-continuity, 2-momentum, 3-energy, 4-turbulent kinetic energy (TKE) and 5-energy dissipation rate are detailed below:

$$\frac{\partial \rho}{\partial t} + \nabla \times (\rho U) = 0 \qquad [3\text{-}1]$$

Where ρ is density, *t* is time, and *U* is the fluid velocity vector.

$$\frac{\partial(\rho u)}{\partial t} + \nabla \times (\rho u u) = -\nabla p + \nabla x\,(\mu \nabla u) - \nabla \times \tau_t \qquad [3\text{-}2]$$

Where *p* is the pressure, *g* is a vector of gravitational acceleration, *μ* is molecular dynamic viscosity, and τ_t is the divergence of the turbulence stresses, which accounts for auxiliary stresses due to velocity fluctuations.

$$\frac{\partial(\rho e)}{\partial t} + \nabla \times (\rho e u) = \nabla \times \left(k_{eff}\,\nabla T\right) - \nabla \times \left(\textstyle\sum_i h_i j_i\right) \qquad [3\text{-}3]$$

Where e is the specific internal energy, k_{eff} is the effective heat conductivity, *T* is the air temperature, h_i is the specific enthalpy of fluid and j_i is the mass flux.

$$\frac{\partial(\rho k)}{\partial t} + \nabla \times (\rho k u) = \nabla \times \left[\alpha_k \mu_{eff} \nabla k\right] + G_k + G_b - \rho_\varepsilon \qquad [3\text{-}4]$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \nabla \times (\rho \varepsilon u) = \nabla \times \left[\alpha_\varepsilon \mu_{eff} \nabla \varepsilon\right] + C_{1\varepsilon}\frac{\varepsilon}{k}\left(G_k + C_{3\varepsilon}\, G_b\right) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \qquad [3\text{-}5]$$

where G_k is the source of TKE due to average velocity gradient, G_b is the source of TKE due to buoyancy force, α_k and α_ε are turbulent Prandtls numbers, and $C_{1\varepsilon}$, $C_{2\varepsilon}$ and $C_{3\varepsilon}$ are empirical model constants. The Discrete Ordinates (DO) radiation model solves the radiative transfer equation [3-6] for a finite number of discrete solid angles, each associated with a vector direction $\vec{s}$ fixed in the global Cartesian system (x, y, z):

$$\nabla \cdot (I(\vec{r},\vec{s})\vec{s}) + (a+\sigma_s)I(\vec{r},\vec{s}) = an^2\frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I(\vec{r},\vec{s}')\,\varphi(\vec{s}\cdot\vec{s})d\Omega' \qquad [3\text{-}6]$$

where $\vec{r}$ is the position vector; $\vec{s}$ is the direction vector; $\vec{s}'$ is the scattering direction vector; a is the absorption coefficient; n is the refractive index; σ is the scattering coefficient; σ_s is the Stefan-Boltzmann constant (5.672 x 10^{-8} W/m^2-K^4); *I* is the radiation intensity; φ is the phase function, and Ω' is the solid angle.

Boundary conditions: The boundary conditions for the flow study were specified in accordance with the best practice guidelines. The profiles for the airflow velocity U and turbulent kinetic energy (TKE) were imposed at the inlet, with the stream-wise velocity of the incident airflow following the power law with an exponent equal to 0.14 corresponding to flow on a sub-urban terrain [Figure 3-11]. The values of ε of the k-ε turbulence model were determined by assuming the local equilibrium of Pk = ε. Standard wall functions were invoked to all wall boundaries aside from the ground boundary, with the ground having wall functions adjusted for roughness. According to Cebeci and Bradshaw (1977), this must be indicated by a corresponding sand-grain roughness height ks and a roughness constant Cs. The horizontal non-homogeneousness of the ABL was controlled by adapting sand grain roughness height and roughness constant for the inlet profile, adhering to the equation:

$$k_s = \frac{9.793 z_O}{C_s} \qquad [3\text{-}7]$$

where, z_0 is the aerodynamic roughness length corresponding to sub-urban terrain. The values selected for sand-grain roughness height and a roughness constant were 1.0 mm and 1.0, respectively, in accordance with best practice guidelines. The sides and the top of the domain are specified as symmetry, signifying zero normal velocity and zero gradients for all the variables in these boundary zones. Zero static pressure was used for the outlet boundary. The boundary conditions are summarised in Table 3-6.

CFD Domain: If the building height was H, the inlet of the computational domain was 3H away from the building, and the outlet was positioned 15H behind the building, which was derived from Franke et al. (2004). The inlet wind speed profile was defined according to the logarithmic law of the wall for high Reynolds numbers for turbulent flow. All CFD models were sited on the ground surface with roughness height (Ks) = 0.14m and the constant roughness (Cs) = 7, which were derived from Blocken et al. (2007). The simulation models were generated using medium grids and the unstructured mesh that allowed for flexibility in conforming to the complex geometries. The average skewness and the mesh quality for all models are shown in Table 3-7. The turbulent nature of the flow was modelled by the standard k–ε turbulence model and Reynolds Averaged Navier Stokes equations (RANS), which are well established in the field of fluid dynamic and heat transfer parameters (Bottillo et al., 2014, Mavriplis, 1999).

Solution convergence: The solution convergence was monitored, and the solution was considered complete upon observation of no significant change between iterations. Moreover, property conservation is also verified if attained. This was conducted by performing a mass flux balance for the converged solution. This option is available in the FLUENT flux report panel, which permits the computation of mass flow rate for boundary zones. For this study's simulation, the mass flow rate balance was below the required value or < 1% of the smallest flux through the domain boundary (the inlet and outlet).

Materials: Although the geometries of the CFD simulation models were duplicated from the dynamic thermal simulation models [Figure 3-9], the entire building envelopes for the CFD models were defined as timber material properties and the ground surface to be of gravel-filled soil. The raised floor and air infiltration were not considered in the CFD simulations. The material properties used in the CFD simulations are shown in Table 3-8.

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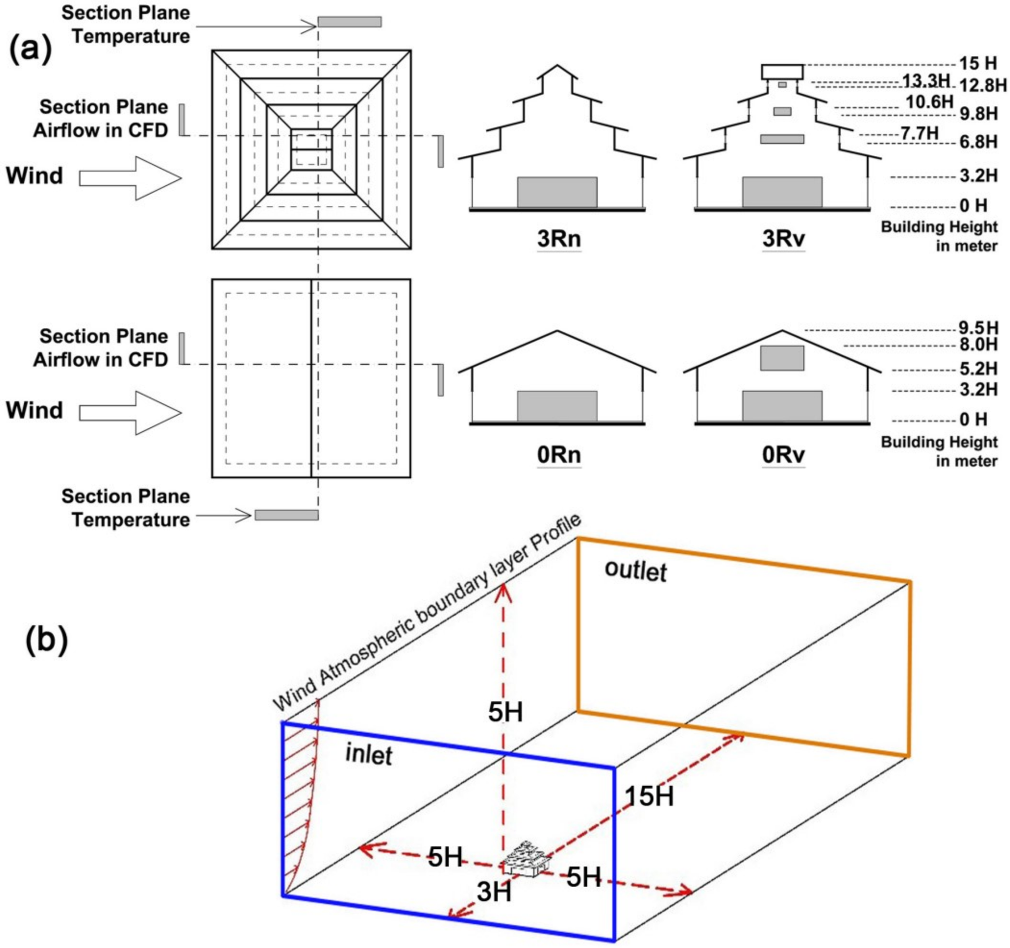

Figure 3-10. (a) Two building typologies used in the CFD simulations (b) Perspective view of the computational domain

Microclimate data: The simulation time and date were selected from the location of Myanmar – the longitude of 21.96°N, the latitude of 96.09°E and the UTC of + 6:30. The intensity of the solar radiation, air velocity, turbulent air intensity, ambient temperature and the ground roughness conditions were set based on available weather data. The boundary temperatures of the building fabric and the initial temperatures were assumed to be the same outdoor dry bulb temperature. The typical weather file of Mandalay showed that 24.61% of the annual hours fell between the temperature range of 30°C and 36°C, which can be considered a high-temperature range. For instance, the CIBSE Guide A (2015) recommends that the internal operative temperature should not exceed 30°C in a free-running building (CIBSE, 2015). In order to understand a high outdoor air temperature range effect on its related indoor air temperature and airflow, two temperature variables – 30°C and 36°C – were used in the CFD simulations. The ASHRAE Standard 55 (2013) recommends that the acceptable operative temperature limit in occupant-controlled, naturally conditioned spaces can be increased up to 2.2°C at the average airspeed of 1.2 m/s (ASHRAE, 2013). The typical weather file of Mandalay showed that 26.79% of the annual hours had wind speeds of between 0.15m/s and 1.2m/s, while 33.56% of the annual hours had wind speeds of between 1.2m/sand 3m/s. Therefore, two variables of wind speeds (1.2m/s and 3m/s) were considered for use in the CFD simulations. Regarding the radiation models, two sets of the macroclimate entities [Table 3.9] were considered, which referred to the typical weather year data of Mandalay. Therefore, the CFD simulation experiments were set to compare 32 isothermal scenarios – two roof typologies for two ventilation modes (with gable vents or without gable vents), two temperature variables (30°C and 36°C as initial temperatures), two wind speed variables (1.2m/s and 3m/s), and two radiation conditions.

Table 3-6. Summary of the CFD model boundary conditions

Boundary condition	Set value
Algorithm	Simple
Time	Steady-state
Solver type	Pressure based
Discretization Scheme	Second-order upwind
Turbulence model	Standard k-epsilon
Near wall	Standard wall functions
Velocity inlet	ABL profile (see Figure 3-11)
Pressure outlet	0 Pa

Table 3-7. Mesh characteristics of the buildings for CFD simulations

Buildings	Gable Vents contained	Elements	Nodes	Average skewness	Average orthogonal quality
3Rv	Yes	1015111	1408084	0.251	0.747
3Rn	No	1463635	2032705	0.241	0.757
0Rv	Yes	1599544	2226556	0.228	0.771
0Rn	No	1556506	2168641	0.227	0.772

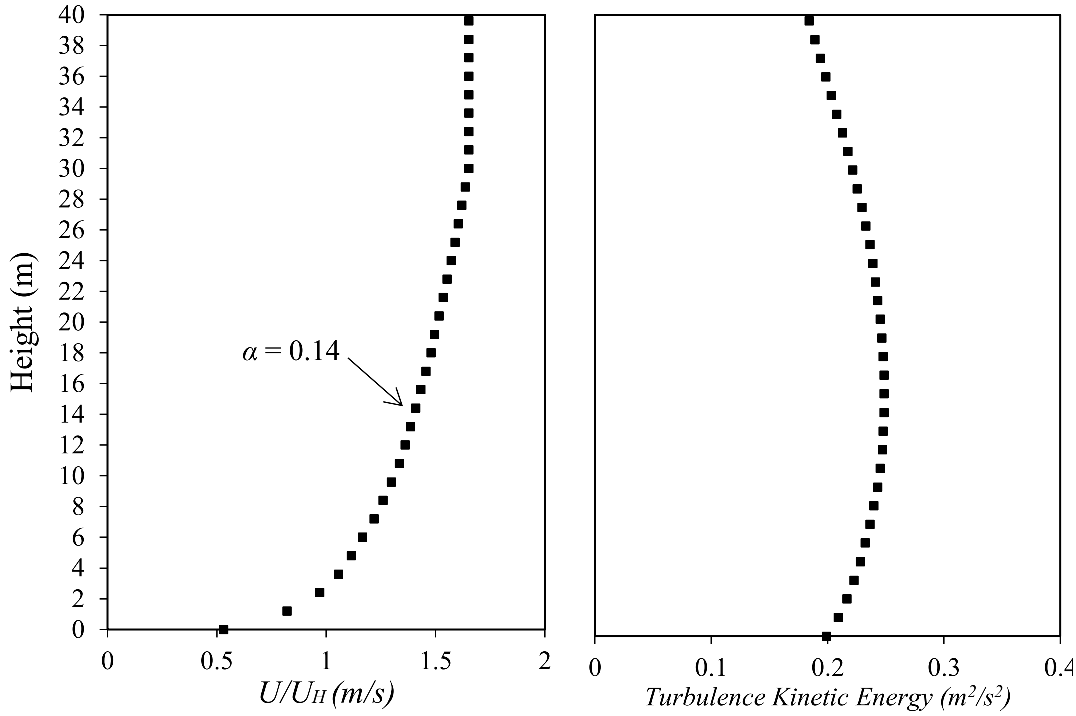

Figure 3-11. Atmospheric boundary layer (ABL) profiles (a) Velocity profile; (b) Turbulent kinetic energy profile of approach wind flow (Blocken, 2015)

Table 3-8. Material properties of air and building materials used in CFD simulations

Material properties	Air	Timber (Building)
Density (kg/m^3)	1.23	900
Cp (Specific heat) (j/K-.kg)	1006.43	2000
Thermal conductivity (w/m-k)	0.024	0.13

Table 3-9. Macroclimate entities for the radiation model used in the CFD simulations, data from typical weather file of Mandalay

Microclimate parameters	High radiation condition	Low radiation condition
Direct Normal Radiation (Wh/m^2)*	892	475
Diffuse Radiation (Wh/m^2)*	604	461
Sky cover (%)	0	50
Temperature variables	30°C and 36°C for both high and low conditions	
Wind speed variables	1.2 m/s and 3 m/s for both high and low conditions	

* Irradiation, the sum of irradiance over a time period, is the amount of solar energy falling on a unit area over a stated time interval which is expressed in Wh/m^2.

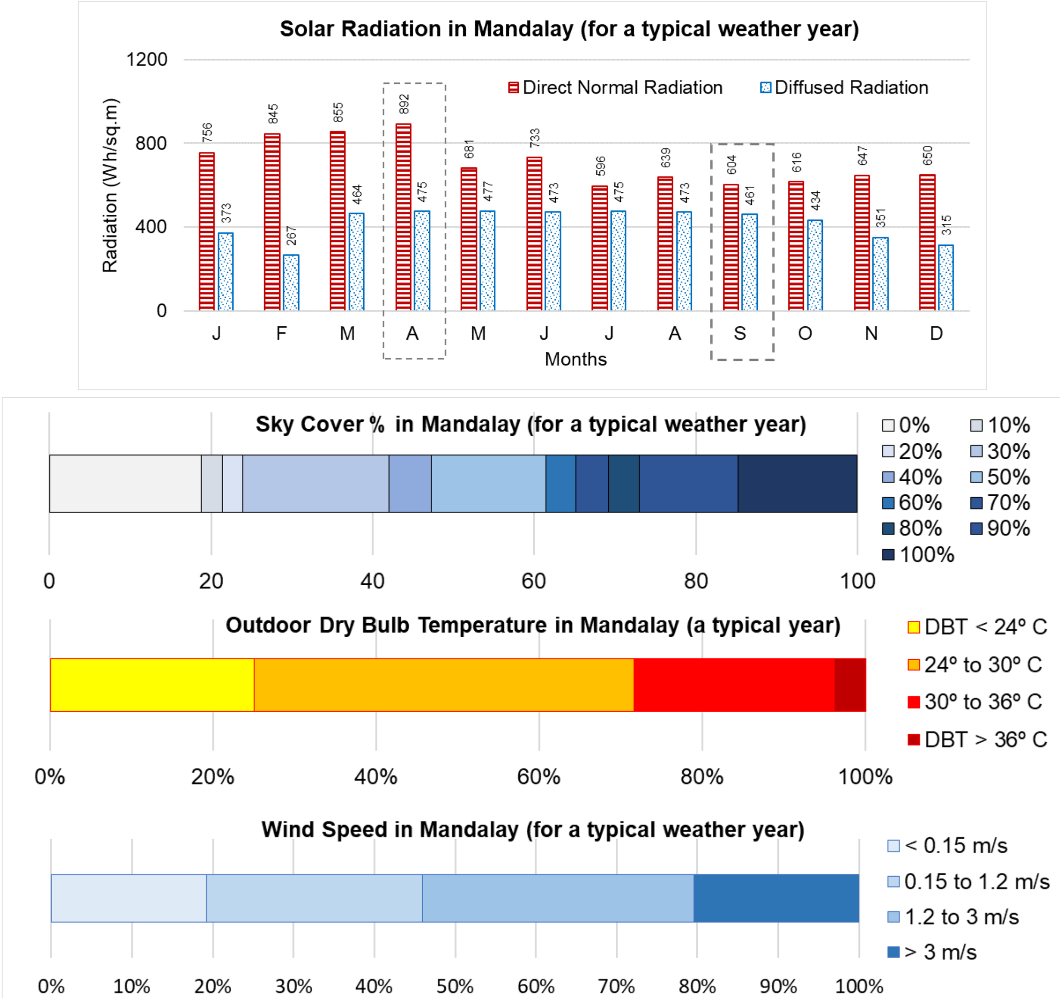

Figure 3-12. Microclimate entities of Mandalay in a typical weather year (Huang et al., 2014)

3.2.2 Simulation results

The results of IESVE simulations were presented on an annual basis, illustrating the indoor air temperatures for the three building typologies. The results of the CFD simulations were illustrated as indoor air temperature and indoor airflow for the two building typologies. Note that the percentage of the annual hours in the results was defined as the percentage of the annual hours of a year, which is 8760 hours for 100%.

3.2.2.1 Simulation results from IESVE

Annual air temperatures: Figure 3-13 presents the results of the 24 scenarios that were generated for the indoor air temperatures of the occupied zones on an annual basis, based on a typical weather year of Mandalay. For the buildings with the material set-1, small differences between the outdoor and indoor air temperatures revealed that the indoor thermal environment of the simulated building had a close relation to the weather outdoors. On the contrary, there were considerable differences between the outdoor and indoor air temperatures in the results of the buildings with the material set 2. Virtually identical results from the two material sets showed that the maximum air temperatures of all buildings were negligibly different but the minimum air temperatures of the buildings with material set-2 were higher than those with material set-1.

For instance, in Figure 3-13, the building 0Rn reached the maximum air temperature of 41.4°C while the building 3Rn reached 41.38°C in the results of material set-1 (ceiling added mode). Similarly, the building 0Rn reached the maximum air temperature of 40.16°C while the building 3Rn reached 40.01°C in the results of material set-2 (ceiling added mode). The material set-2 contained a cool roof effect from which the buildings could better offset the peak outdoor dry bulb temperature than the buildings with material set-1 were able to. Moreover, the buildings with material set-2 received shorter quartile lengths and higher median and mean values than the buildings with material set-1. It was also found that the values of the upper extremes for all scenarios were above 31°C. Therefore, the percentage of the annual hours above indoor air temperatures, with 31°C and 36°C as extreme cases, was considered at the next step.

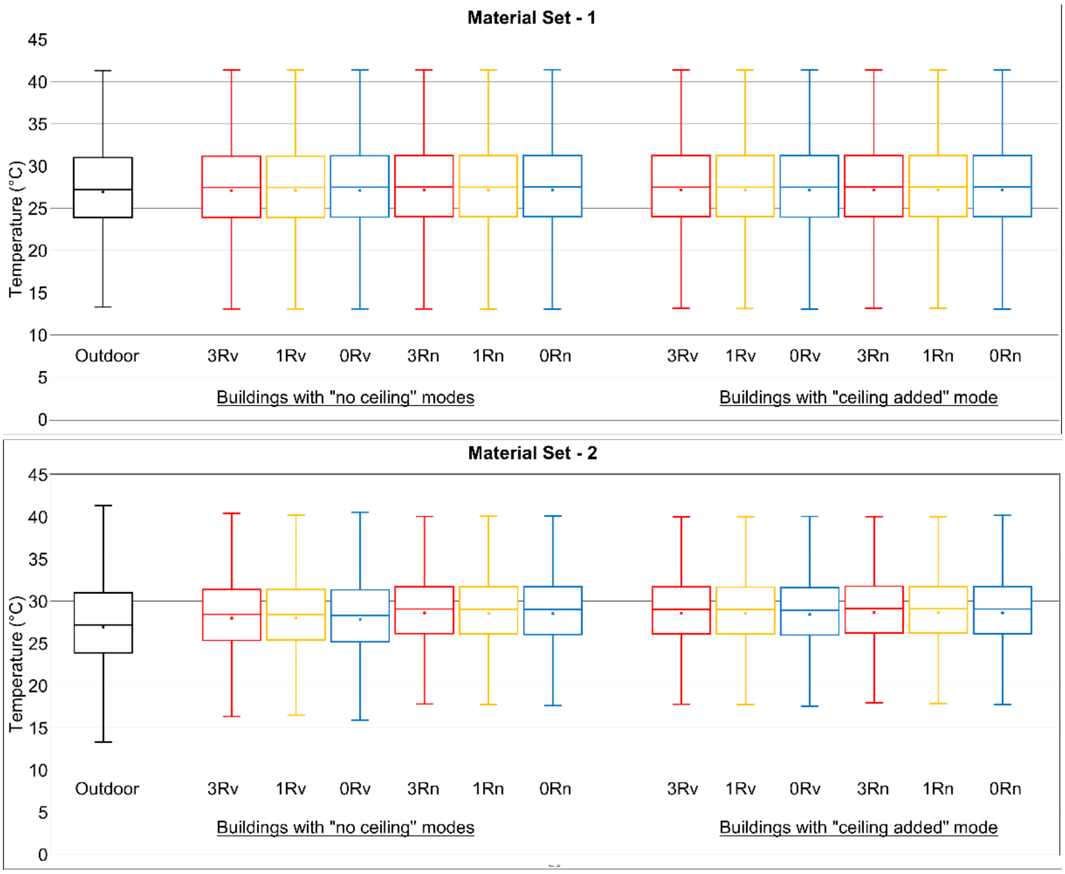

Figure 3-13. Air temperatures of the 24 scenarios simulated using a typical weather year for Mandalay

Air temperatures above 31ºC and 36ºC: Figure 3-14 indicates that the buildings with material set-2 received a higher percentage of the annual hours above indoor air temperature 31°C and maintained the lower percentage of the annual hours above indoor air temperature 36°C. Conversely, the buildings with material set-1 experienced a lower percentage of the annual hours above indoor air temperature 31°C and maintained a higher percentage of the annual hours above indoor air temperature 36°C. The percentages of the annual hours above 31°C and 36°C were increased in the buildings if there were no gable vents.

For instance, for the buildings with no ceiling in the material set-2, 31°C was found in the building 3Rv for 27.31% of the annual hours above indoor air temperature, but this changed to 30.81% in the building 3Rn, as 3.5% difference. Moreover, the results of both material sets showed an increased percentage of air temperatures above 31°C and 36°C in all buildings when the ceilings were added, but the gable vents were excluded. The results of Figure 3-13 and Figure 3-14 were generated for the occupied spaces, and the building geometries, internal gains and window opening times were fixed. Therefore, those different results of indoor air temperatures were due to the impacts of roof typologies, roof ventilation, ceiling modes, and building materials.

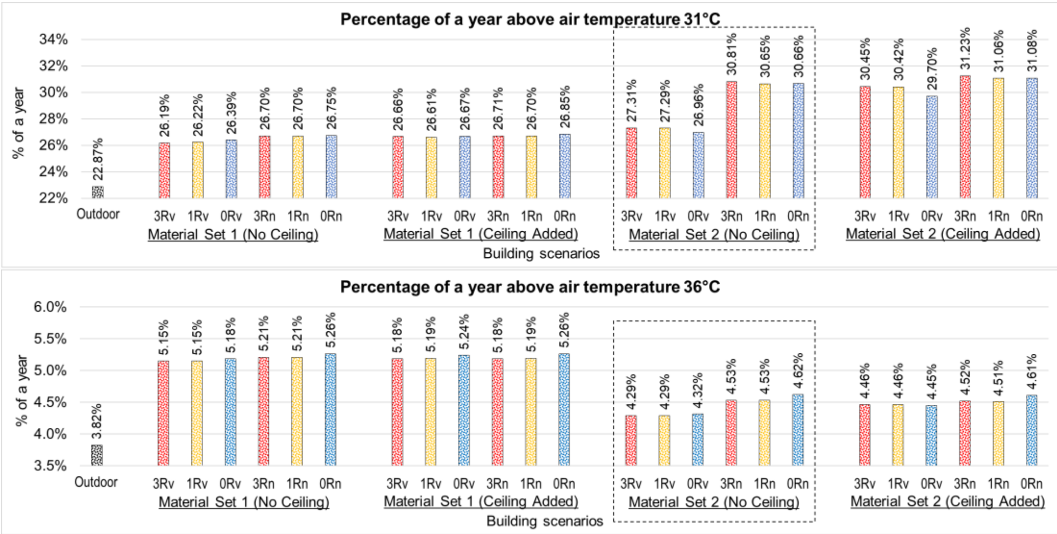

Figure 3-14. Air temperatures above 31ºC and 36ºC at the occupied spaces of each building, a typical weather year for Mandalay

Peak air temperatures: The results of Figure 3-15 were generated from the indoor air temperatures of all intermediate roof levels from the day when the air temperature reached the maximum value in a typical weather year. The results showed that the indoor air temperatures of the roof spaces were higher than the occupied space. As there were no internal gains in the occupied spaces of all buildings, a high indoor air temperature of roof spaces was due to its direct contact with the solar heat gain above the roof and the upward buoyant force of the hot air. Although the results of the buildings' indoor air temperatures of occupied space were unnoticeably different in all scenarios, their indoor air temperatures of roof spaces were significantly increased, but the increments were different due to ceiling mode, ventilation modes and building materials. In both material sets, the indoor air temperatures of roof spaces unnoticeably dropped when the ceilings were added but considerably increased when the gable vents were excluded. In both material sets, if the buildings had gable vents, the resultant indoor air temperature was lower in building 0Rv than in building 3Rv.

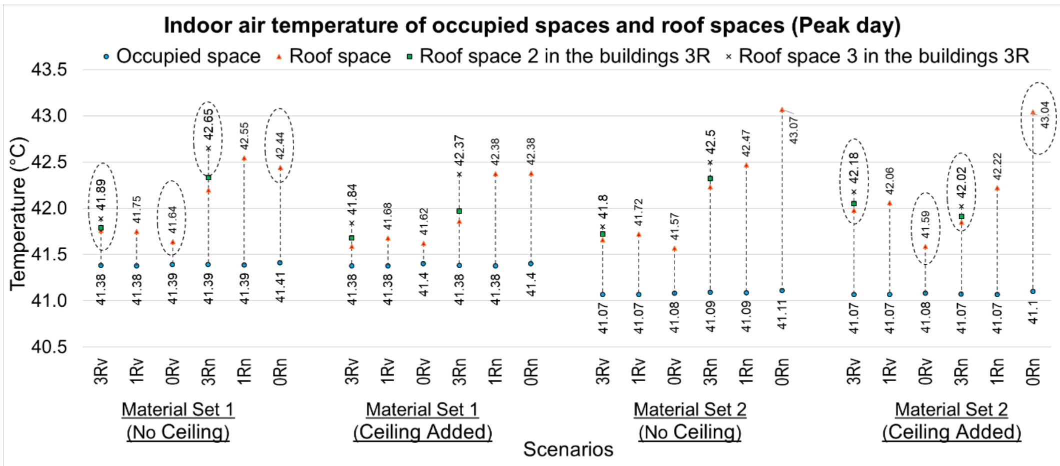

Figure 3-15. Indoor air temperatures of occupied space and roof spaces of each building – results for the day when the air temperature reached a maximum for a typical weather year

On the contrary, in the material set 2, if the gable vents were excluded from the models, the building 0Rn resultant roof space's indoor air temperature was higher than in building 3Rn. For instance, as shown in Figure 3-15, in the material set-1 without ceiling mode, the roof space's indoor air temperatures of building 3Rv reached 41.89°C and of building 0Rv reached 41.64°C; building 3Rn reached 42.65°C while the building 0Rn reached 42.44°C. In the material set-2 with the ceiling added mode, the roof space's indoor air temperatures of building 3Rv reached 42.18°C, and building 0Rv reached 41.59°C; building 3Rn reached 42.02°C while building 0Rn reached 43.04°C.

3.2.2.2 Simulation results from CFD

This section presents the results of the 32 isothermal scenarios that were investigated using CFD simulation; the results were generated from the vertical planes of each building with 1m interval that allowed us to compare the changes of indoor air temperatures and airflows along with the building height. The vertical planes of temperature profiles were generated using a normal angle at the inlet wind direction. The vertical planes of airflow profiles were generated from the plane, which was parallel to the inlet wind direction.

Roof typologies: Figure 3-16 presents the indoor air temperatures' profiles and airflow profiles of two building typologies in which two ventilation modes were compared for the microclimate variables 36°C (temperature) and 3m/s (wind speed) from the vertical planes. Selecting samples for a high temperature (36°C) and wind speed (3m/s) for Figure 3-16 allowed us to compare significant turbulence indoor airflow and temperature changes along the vertical planes. The results showed that the indoor air temperatures of the building 3Rn were lower than those of the building 0Rn up to 2.5m height. For instance, the indoor air temperatures were found at 2m height as 37°C in the building 3Rn and at 38°C in the building 0Rn. However, along the vertical planes, 2.5m onward, the building 3R maintained a higher indoor air temperature than the building 0R. On the contrary, the indoor air temperatures of the building 3Rv were found to be 43.6°C at 13.5m height (near the roof), and the indoor air temperatures of the building 0Rv were found to be 38.4°C at 9m height (near the roof), from which the roof's space temperature difference was found to be 5.2°C.

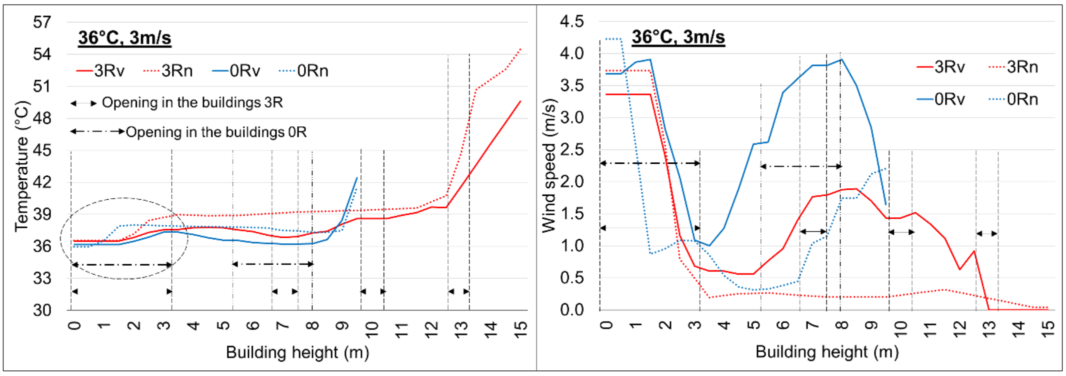

Figure 3-16. Indoor air temperatures profiles and airflow profile of two building typologies with two ventilation modes at high radiation conditions of the observed vertical planes

It was also clear that the lack of gable vents caused high indoor air temperatures. For instance, the indoor air temperatures of the building 3Rv were found to be 43.6°C at 13.5m height (near the roof); at that time, the indoor air temperatures of the building 3Rn was found to be 50.7°C. Unlike temperature profiles, significant differences between the buildings with gable vents and without gable vents were found in the wind speed profiles. The different profiles of buildings 3Rn and 0Rn revealed that the impacts of building height and roof typologies had greater impacts on the airflow profiles than on the temperature profiles. The upstream airflow of building 0Rv reached about 8m in height, where there was a large area of gable vent; however, the airflow instantly dropped near the roof. On the contrary, the airflow in building 3Rv accelerated along with its location of gable vents but created a lower airflow than building 0Rv attained, the lowest of which was near the roof.

Indoor air temperatures: The indoor air temperature profiles shown in Figure 3-18 were generated for a high radiation condition for two building typologies with two ventilation modes. In all buildings, the indoor air temperatures were significantly inclined from about 2.5m height onwards. The results revealed that there was a temperature increment at the top of the roof and boundary of the envelope, which was indicated with green and light blue colours. The results showed that the indoor temperatures at the lower height of the building 3R were closely related to its initial temperatures and the outdoor microclimates than was the case with building 0R. For instance, at the outdoor microclimate scenario, 30°C with 1.2m/s, the indoor temperatures of the building 0Rn and building 3Rn were 32.4°C and 31°C, respectively at 1m height. Among all results, the building 3Rn with a low airspeed for the outdoor microclimate showed the worst-case scenarios. For instance, the indoor air temperatures of the building 3Rn were found to be 56°C at 14m height (near the roof) for 36°C, 1.2m/s scenario.

Indoor airflow: Following the same approach presented for the indoor air temperature profiles, the indoor airflow profiles shown in Figure 3-19 were generated for a high radiation condition. The results revealed that there was scope for air turbulence in the buildings with gable vents. The results also showed that the speed of indoor airflow dropped beyond the opening height of building 3Rn that even caused very still air conditions near the top of the roof. Unlike building 3Rn, some turbulence was found at the top of building 0Rn. When there was wind flowing through the gable vents, turbulent conditions were found in both buildings 3Rv and 0Rv aligned with the height of the gable vents. For instance, in building 3Rv for the profile of 36°C with 3m/s, the speed of indoor airflow dropped to 0.6m/s at 4m height but increased to 1.9m/s at 8.5m height. Although both buildings 3Rv and 0Rv had the same indoor air volumes and gable vent areas, a greater airflow can be observed in the building 0Rv, which was caused by a single inlet of wind.

Radiation models: Figure 3-17 compares the results of two radiation conditions for the building 3Rn (solid lines for low radiation conditions and dash lines for high radiation conditions), where the intensity of radiation was differentiated by the values of sky cover, direct normal radiation and diffuse radiation. In the same building, if the initial temperature, the outdoor dry bulb temperature and wind speed were fixed, the scenario with a low radiation condition received a lower indoor temperature than the scenario with a high radiation condition. If the occupied spaces were considered for 2m height, for the profile of 30°C with 1.2m/s, the indoor air temperature was found to be 31.5°C in low radiation conditions, it changed to 32.2°C in the high radiation conditions that caused 0.7ºC difference. The more the building height increased, the higher the temperature increment was found between two radiation conditions. For instance, for the profile of 30°C with 3m/s, the indoor air temperature of low radiation conditions was found to be 34.2°C at 12m height, but the indoor air temperature of high radiation conditions was found to be 32.6°C at 12m height, which caused a 1.6ºC difference. For the profile of 36°C with 3m/s, the indoor air temperature of low radiation conditions was found to be 40.2°C at 12m height, but the indoor air temperature of high radiation conditions was found to be 38.6°C at 12m height, causing a 1.6ºC difference. When the two radiation conditions were compared, a small temperature difference (0.7ºC) was found when the outdoor microclimate entities were 30°C with 1.2m/s, but a large temperature difference (1.6ºC) were found when the outdoor microclimate entities were at 30°C with 3m/s and 36°C with 3m/s. The results of the temperature differences between the two radiation conditions revealed that there was a considerable heat gain from the solar radiation in the studied climate.

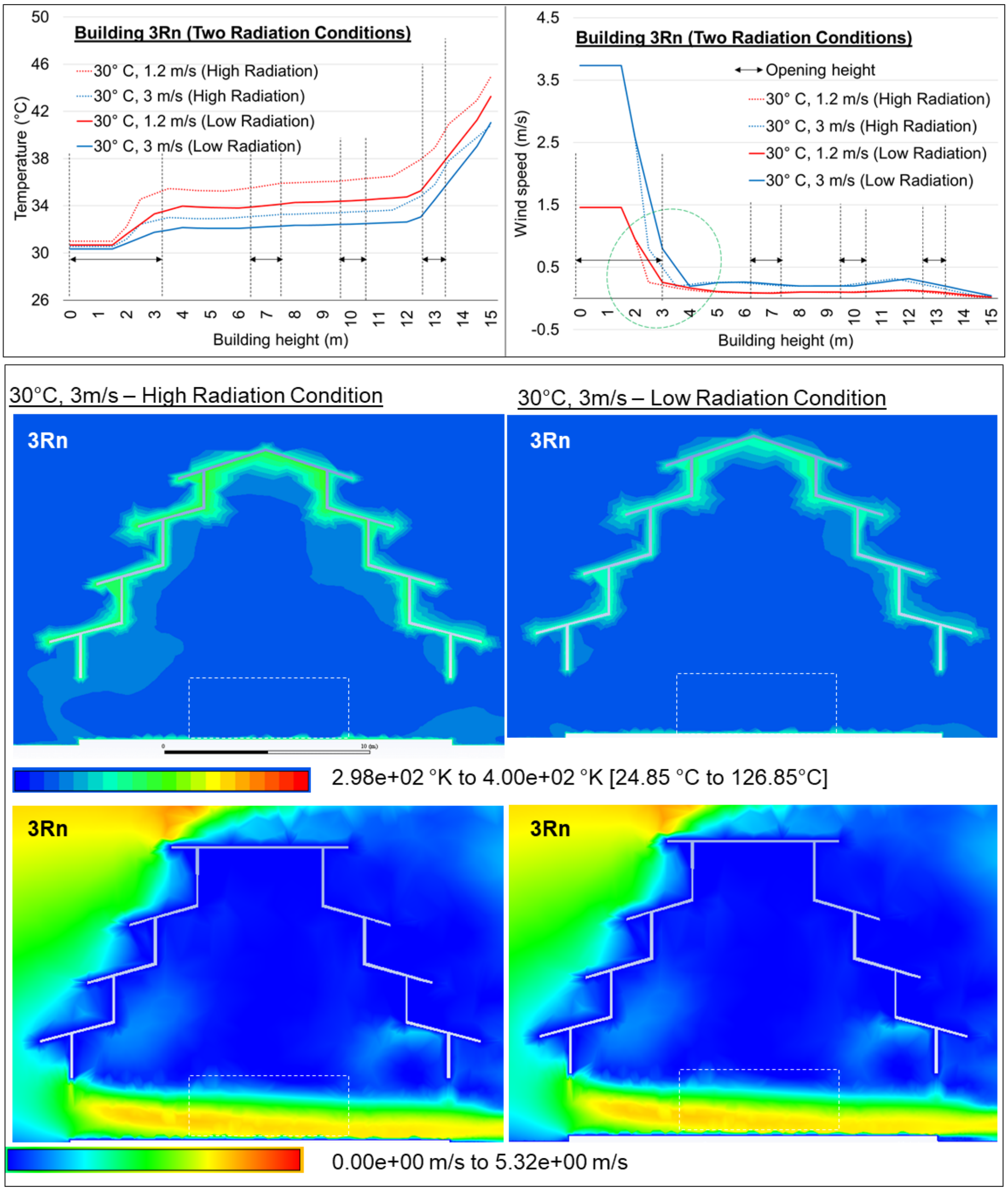

Figure 3-17. Comparison of high and low radiation conditions for the building 3Rn

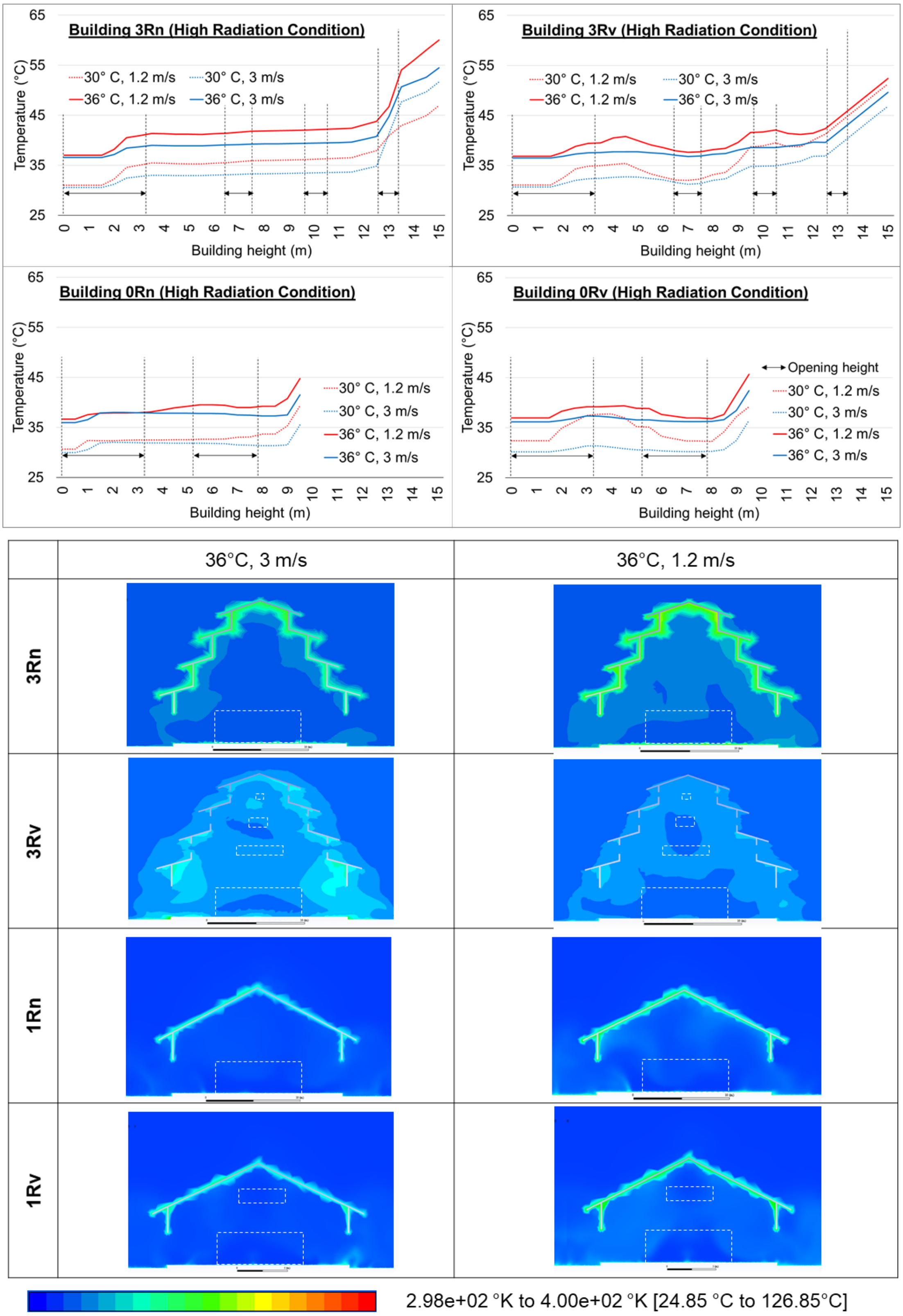

Figure 3-18. Indoor air temperature profiles of two building typologies with two ventilation modes considering high radiation conditions on the observed vertical planes

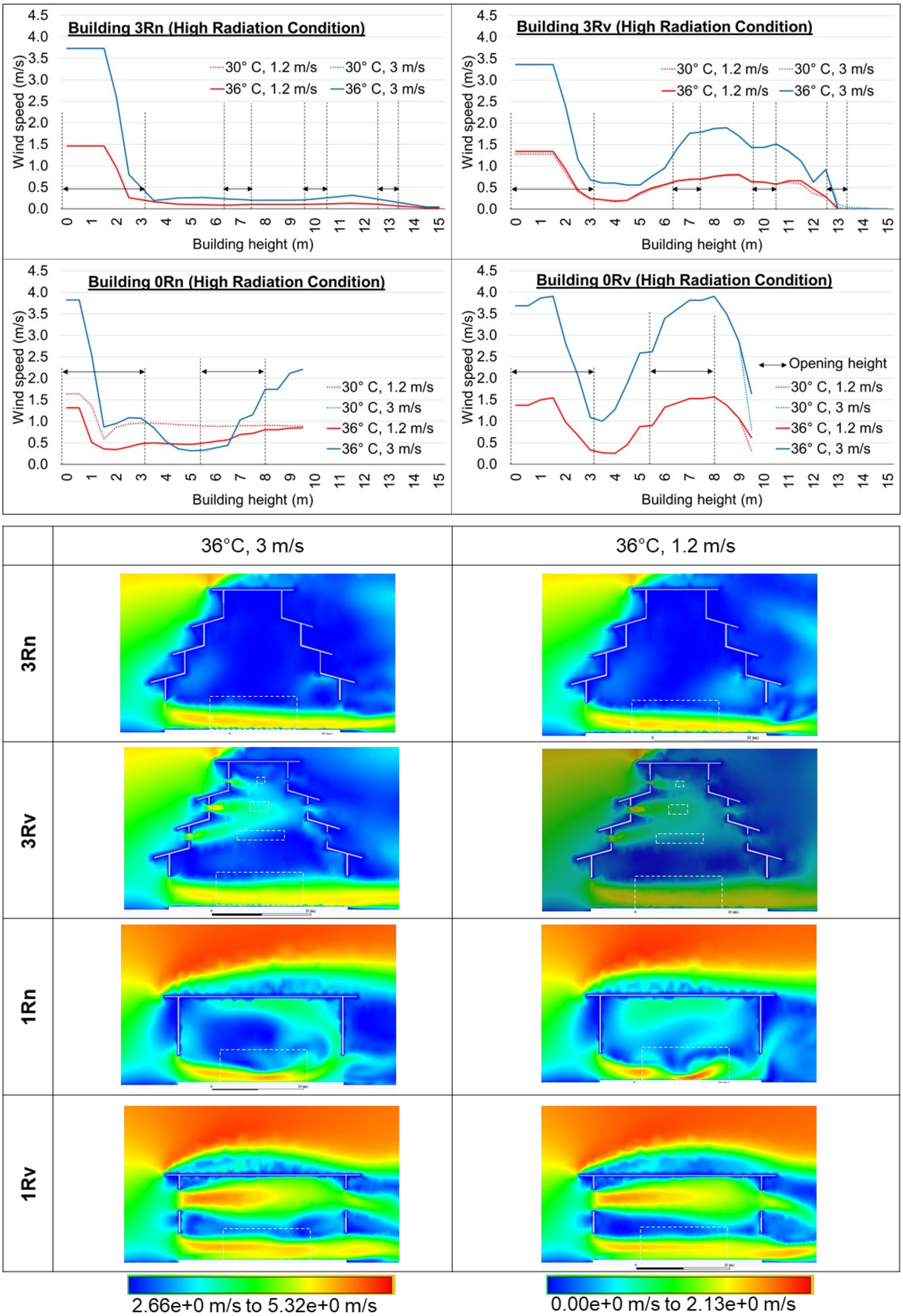

Figure 3-19. Indoor airflow profiles of two building typologies with two ventilation modes considering high radiation conditions on the observed vertical planes

3.2.3 Discussion

The factors that impact the resultant building microclimates considering the prescribed scenarios and combinations of conditions are complex. Therefore, the findings for the key questions were grouped under headings, as follows.

Roof typologies and roof ventilation: In the IESVE simulations, building 3Rs presented a higher annual mean and median value but a lower maximum air temperature than building 0R [Figure 3-13]. Moreover, the occupied space of the building 3R maintained a slightly lower percentage of the annual hours above air temperature 31°C and 36°C than the buildings 1R and 0R when using the material set-1 [Figure 3-14]; however, differences in their results were negligible when roof typologies were considered. Regarding the roof space's air temperature, building 3R presented higher temperatures than building 0R regardless of gable vents modes in both material sets [Figure 3-15]. In the CFD simulations, the results showed that the indoor air temperatures of building 3Rn were lower than those of building 0Rn up to 2.5m height; however, along the vertical planes from 2.5m onward, building 3R maintained a higher indoor air temperature than the building 0R did [Figure 3-16]. The CFD results also showed that the building 3R maintained a higher indoor air temperature than the building 0R along the vertical planes of 2.5m onward. On the other hand, the results of all building typologies showed that the indoor air temperatures were increased near the roof space; the results are a good agreement with the field study of the Dutch Colonial buildings in Indonesia. Wibowo et al. (2018) measured the vertical distribution of air temperature under the different ventilation conditions; for a building with 5.6m height, it was found that the temperature near the ceiling was 30.2°C when the temperature near the floor was only 21.7˚C. In Figure 3-18, a notable indoor high temperature of 56°C was observed near the roof of the building 3Rn due to its lack of roof ventilation, predominant roof height and large building layout. It is not a surprising fact for the tropical climate. For instance, Zakaria et al. (2018)'s study showed a steep temperature gradient in vertical temperature distribution at the courtyard of the traditional Chinese Shophouses in Malaysia, where the measured temperature was found a high as 51.6˚C near the roof. Note that an inner courtyard (air-well) is placed midway between the front and rear of the house, but the courtyard is covered with a roof, but it has roof ventilation. In this study, both IESVE and CFD simulations demonstrated good agreement, but findings conflicted for the building 3R, the traditional building with the multistage roof had lower air temperature up to 2.5m height but a higher roof space air temperature compared to the buildings with a single gable roof.

Building materials: Distinct outcomes were observed between the material set-1 (thatch roof and timber walls) and material set-2 (metal roof and brick walls) considering annual air temperatures in the occupied spaces [Figure 3-13]. The material set-1 contained lightweight vernacular materials such as timber. The buildings with material set-1 presented a high percentage of the annual hours above 36°C [Figure 3-14], which revealed that buildings with vernacular materials might be vulnerable to high and extreme temperature conditions. The results presented for the material set-1 are in agreement with the study by Nicol et al. (2005): if buildings have poor insulation characteristics or are lightweight, with low thermal capacity, they are likely to produce uncomfortable indoor temperatures during hot summers, as the indoor thermal environment of lightweight building envelope could closely optimise the weather outdoor. The material set-2 contained a cool roof effect with less solar absorptance value (high reflectance) and high thermal capacity in the walls. Regardless of the differences in roof typologies, the use of material set-2 caused a higher annual mean temperature and a higher minimum air temperature in the occupied spaces [Figure 3-13]. Therefore, the buildings with material set-2 presented a higher percentage of the annual hours above 31°C but a lower percentage of the annual hours above 36°C than the material set-1 [Figure 3-14]. In agreement with this, two years of continuous monitoring work undertaken in Italy also revealed that the buildings with cool roof effect had better capability to offset a higher outdoor dry bulb temperature than a roof with high solar absorptance (Pisello and Cotana, 2014). The highest indoor air temperature in the roof spaces of building 0Rn was observed in the results of material set-2; however, in both material sets, the highest indoor air temperature was observed in the roof spaces of the building 3Rv compared to the building 0Rv [Figure 3-15]. The simulation results from IESVE revealed that the thermal performances of the studied buildings were more altered by the building envelope materials and roof ventilation mode rather than by roof typologies.

Response to tropical climates: Roof ventilation and roof typology play roles in removing hot air from a naturally ventilated building in the tropics. In this study, the CFD results suggested that building 3R could keep a lower air temperature up to 2.5 metres in height. The results also demonstrated temperature differences between two radiation conditions, revealing considerable heat gain from the solar radiation in the studied climate [Figure 3-17]. This suggests that the buildings with multistage roofs have the benefit of being able to reduce the incidence of radiated heat gain. However, in order to avoid high air temperature in the roof space, gable vents should be used to remove the hot air. Ameer et al. (2016) revealed that a narrowed roof in a building excels in providing a lower mean age of air and higher air change effectiveness and also creates a considerable roof height and less internal air volume. A similar concept was found in Myanmar's traditional buildings with a multistage roof that uses an abstract roof curve to reduce the size of intermediate roof structures. Furthermore, one should not forget that the buildings with multistage roofs enable the relocation of the gable vent to the centre of the buildings, which allows for the quicker removal of hot air quickly. In addition to the roof form, the simulation results revealed that the use of gable vents would be more effective in the buildings with multistage roofs if their building envelopes have material set 2.

The uncomfortably high air temperature in roof spaces revealed why the roof spaces of the ancient Myanmar buildings were unoccupied. A similar study done in the CFD simulations, which investigated the indoor air quality and thermal performance of a windcatcher building, showed a high air temperature near the top of the building (Calautit et al., 2020). Although the roof spaces of the buildings with multistage roofs were inherently vulnerable to overheating, the results of this study inform us that the indoor air temperatures of the occupied spaces for all simulated buildings closely responded to the outdoor air temperatures. Although the buildings with multistage roof have roof ventilation for passive cooling, the occupied spaces of the buildings with multistage roofs might be at risk of thermal discomfort because of both extreme summer overheating and increased annual mean air temperature due to the pervasive threat of the climate crisis. Similar results for Geodesic dome building in hot climates also revealed that natural ventilation using roof vents could not satisfy thermal requirements during hot summer periods, and complementary cooling solutions should be considered (Soleimani et al., 2016).

Limitations: Hitherto, very limited literature was found for the thermal performance design strategies used in Myanmar's vernacular architecture. Therefore, this study might be one of the first to investigate the effects of the present climate conditions on the thermal performance of buildings with multistage roofs. It was impossible to capture the rich diversity of Myanmar cultures and customs within two simulation experiments presented in this study; however, it was necessary to set the workable scope to investigate the difference between the buildings with a multistage roof and the buildings with a single gable roof in terms of their thermal performance. With this pressure in mind, the results of both simulations were generated as a single zone for the entire building with various prescribed, fixed assumptions. It is necessary to note acknowledge other limitations of this study as follows.

In both simulation studies, the size and shape of the buildings were treated as equal length and width, and 1.5m eave for roof shading. It is also important to note that the aim of using the sample size of buildings in this study was to compare differences between three-stage multi-tier roofs and a single gable roof; therefore, a more realistic roof size for Myanmar's traditional building might be considered for application.

The weather file used in the IESVE simulations was unable to generalise to the whole country as Myanmar extends through 18 degrees of latitude that results in different climate zones. The CFD simulations were generated by using an isothermal situation; therefore, the exterior air temperature fluctuation, natural wind direction, and wind speed changes over time were out of the scope of work for the CFD simulations. All these factors were difficult to put together in one study, yet nevertheless are important considerations for the building microclimate. Although the simulation theories used in this study were well-established (Blocken et al., 2007, Bottillo et al., 2014, Franke et al., 2004, Huang et al., 2014, IESVE, 2015, Mavriplis, 1999), ideally, input data and results should be validated with real-world data, for which further studies are necessary. Nevertheless, the simulation studies presented in this study can be a platform for further Myanmar vernacular architecture research, both for the art and history, the building thermal performance design and building microclimates for the present climates.

3.2.4 Findings

When investigating the thermal performance of buildings with multistage roofs, several building parameters and microclimate conditions should be considered, as well as their impacts on indoor air temperatures and airflow. In the present study, three buildings typologies with two ventilation modes were used to compare the impacts of building materials and different microclimate variables on indoor thermal performance. When evaluating the thermal performance of the selected roof typologies, distinct results were observed when two different material sets were used; however, the thermal performances of the building with multistage roofs and the building with a single gable roof were more influenced by the use of different ventilation modes.

A summary of findings from this study can be listed as-

- A traditional building with a multistage roof can maintain lower air temperature at the occupied space, but a high air temperature could trap at the roof space, so roof ventilation is essential.
- The use of an abstract roof curve not only allow to divide the number of tiers and but also it can reduce roof (heated) internal air volume near the roof surface, which has direct solar heat gain.
- The building envelope materials and roof ventilation (through the use of gable vents) play a role to alter the thermal performance of the studied buildings, for which it requires further study to improve a better thermal performance for Myanmar traditional building with the multistage roof.

In sum, the results of the study showed that Myanmar's traditional buildings with multistage roofs present several passive designs through its roof typologies, roof height, roof ventilation and building materials which affect building microclimate for the indoor comfort in tropical weather. Therefore, if the grandness of the ancient Myanmar multistage roof is to be appreciated, it is not only because of its fine art and semiotic values; what should also be honoured is its capability to manage the hot, stale air in the roof structure from the use of simple building physics and geometry.

3.3 Conclusion

The studies presented in this chapter contribute in-depth knowledge of vernacular houses and ancient Myanmar vernacular architecture by using a simulation experiment developed from the National Races Village field study and a review of Myanmar traditional buildings with multistage roofs.

Considering the impacts of climate change on Myanmar housing, the simulation results were generated using present and future climate scenario. As Oliver (1986) asserted, the technological merits of vernacular traditions do need to be studied and understood, and the extent of vernacular knowhow does demand to be examined and recognised. This chapter was attempted to fill this research gap, and different vernacular practices in Myanmar housing and traditional buildings by the way they provide thermal comfort were investigated, and it was questioned whether the building thermal performance of Myanmar vernacular housing copes with climate change.

The findings of the vernacular house study (Section 3.1) revealed that the efficacy of traditional passive design techniques would not be sufficient to achieve thermal comfort in the predicted future climate scenario. The findings of Myanmar's vernacular buildings with multistage roofs (Section 3.2) showed that with the use of a typical light-weight permeable envelope, the indoor temperatures followed ambient temperature closely; although a heavier-weight set of materials did not impact significantly on the maximum air temperatures, it made a difference with regard to the lowest temperatures and overall comfort. The variable that impacted the most on the results was roof ventilation mode, with the best results being 3.5% of the annual hours better than the worst. The multistage roof was found to help reduce heat gains from solar radiation.

Changes in the use of building envelope materials were a focus of both studies by comparing vernacular materials (lightweight timber walls with thatch roofs) and their customs in building modern materials (brick walls, metal roof and concrete floors). Three Myanmar climate contexts and their present and future climate scenarios were considered in the simulation. On the other hand, the limitations of both studies were acknowledged. Nevertheless, both findings revealed that there is a need to improve the thermal performance of Myanmar vernacular houses and traditional buildings, in terms of their fabric material properties and ventilation performance for building thermal comfort. In sum, the studies presented in this chapter highlighted that the importance of empirical data sets to generate more reliable scientific facts to improve the passive design techniques of Myanmar vernacular housing with innovative solutions in order to cope with the changing climate. Hence, Chapters 4 and 5 were attempted to fill the research gap of empirical data sets for both vernacular and modern housing in Myanmar.

Overall, this chapter contributes to an understanding of how the use of vernacular materials, layout, and building form can provide thermal comfort in Myanmar housing while identifying challenges concerning current and future climate scenarios (Zune et al., 2019a, Zune et al., 2018a, 2019b).

Acknowledgements: The author acknowledges the co-author Conrad Pantua for the academic input of the CFD simulations.

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If you do not tell

the truth about yourself

you cannot tell it

about other people.

~Virginia Woolf (1882-1941)

from The Moment and Other Essays

[A paper read to the Workers' Educational

Association, Brighton, May 1940]

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4. Assessing Overheating Risk in Vernacular Dwelling through Empirical and Simulation Studies

Customs in Myanmar vernacular housing reflect socio-economic conditions, including building typologies and materials and passive design solutions for thermal comfort. Myanmar's 2014 Census data reported that 38% of dwellings are made of timber, 34% of dwellings are made of bamboo, and 33% of dwellings have thatched roofs (Ministry of Labour, 2015); all of these are considered vernacular materials. Only 16% of dwellings are made of brick and concrete, while 62% have corrugated metal roofs (Ministry of Labour, 2015). The practices of Myanmar housing with vernacular materials seem to have remained remarkably resilient in Myanmar, but no regard is given to how the customs in housing affect thermal comfort and whether they can cope with future climates. The simulation case studies presented in Chapter 3 revealed that vernacular passive design techniques used in Myanmar houses are insufficient to achieve thermal comfort in the present and predicted future climate scenarios. The practical measurement of the building thermal performance of Myanmar housing, on the other hand, is important because the evidence can support the predictions of building thermal performance. Furthermore, accurate knowledge of the thermal performance of Myanmar vernacular housing could cause a shift to develop building thermal performance design for climate change adaption. This was a gap in the current literature and, therefore, the focus of the chapter to assess the building thermal performance of a vernacular dwelling through empirical and simulation studies.

Myanmar has been ranked second out of 183 countries in the long-term climate risk index for the period 1990-2018 (Eckstein et al., 2019, Harmeling et al., 2011), and it continues to be at high risk. The climate shift depicted by Köppen-Geiger climate classification (Figure 1-4) shows that the northern part of Myanmar would face a more noticeable climate shift than the other cities. Located in an outlying subrange of the Greater Himalayan mountain range, northern Myanmar historically (1926-1950) featured a warm temperate climate with winter dry and warm summer (Koppen climate Cwa). It predicts that the climate Cwa of northern Myanmar is likely to be replaced by an equatorial winter dry climate (Koppen climate Aw) in 2076-2100 due to global trends in observed climate and projected climate change scenarios (Rubel and Kottek, 2010). Therefore, for the case study presented in this chapter, the monitored dwelling was selected from a rural area of Myitkyina city in northern Myanmar. Section 1.1.2 presents the characteristics of the city and its climate context.

One naturally ventilated brick-nogging dwelling with a metal roof was selected to access the overheating risk in one of typical Myanmar dwellings. Note that one of the notable customs in Myanmar vernacular dwelling from the past to the present time is the roof material - from thatch roof to metal roof. Whilst the monitored dwelling and simulation models may not be representative of the vernacular dwellings in Myanmar in the past, it does represent passive design strategies, the fundamental construction materials used, and the building envelope performance for the studied climate in the present days. This study attempted to fill the knowledge gap by presenting:

- the analysis of the indoor thermal environment data sets from the monitored dwelling compared to the weather outdoor from the historic stations,
- the validation between the indoor thermal environment data of the monitored dwelling and simulation models to undertake the simulation experiments for the predicted future climate scenario, and
- the analysis of the indoor thermal performance of the monitored dwelling with different modern customs of building envelope materials.

The model utilised existing weather data and morphed weather data representing future climate change scenarios. Besides investigating the building thermal comfort of the monitored dwelling, the impacts of building envelope materials on building thermal performance were a focus of simulation studies in this chapter by comparing typical construction with vernacular materials found locally in order to understand their role in the resultant building performance. The data sets were analysed using wet-bulb temperature and heat index equations to comprehend potential heat stress. The research approaches and steps proposed and applied in this study are shown in Figure 4-1.

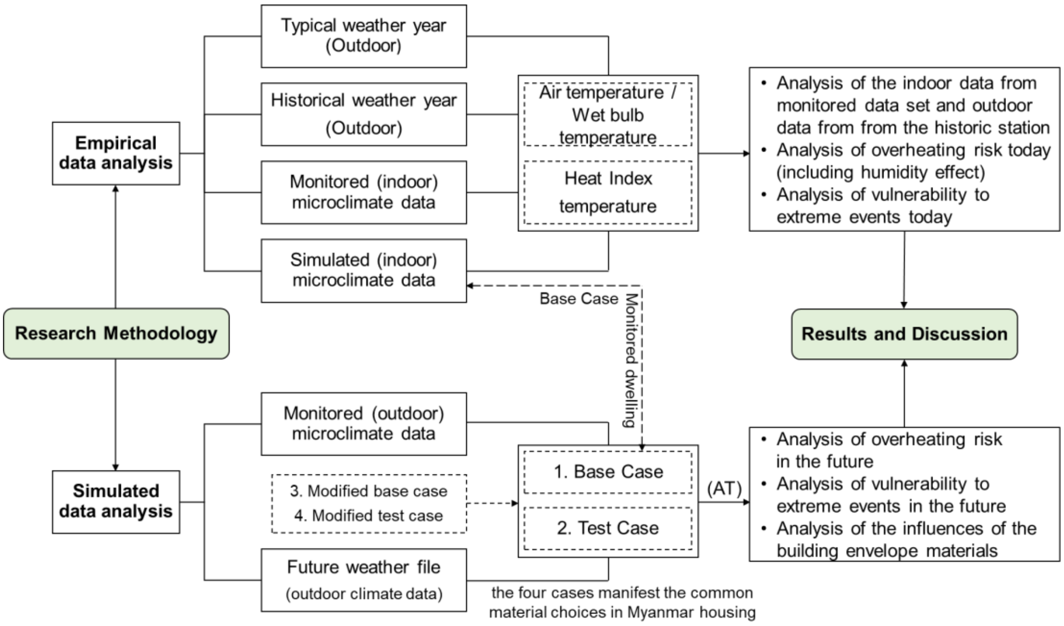


Figure 4-1. Research approaches and steps proposed and applied in this study

4.1 Methodology

This study used one-year monitored data to allow a comparison of the empirical data set and the results of the analytical simulations quantitatively. By doing so, the following data collection method, analysis method, and process of simulation experiments were established for this work.

Monitored dwelling: The monitored dwelling (Figure 4-2) faced almost due north and was adjacent to similar detached houses. The whole building covered an area of about 63 m^2, with a maximum length of 8.4 m and a maximum width of 8.4 m; the total floor area was about 126 m^2. A private office was located at the ground level, where the dwelling envelope was built with brick walls, timber posts, and a concrete floor. Residents lived at the first-floor level, where the dwelling envelope was built with timber floor, timber walls (at the front), and bamboo woven walls (at the side and back). The timber-framed Dutch gable roof was covered with zinc sheets, and small gable vents on the pediments of the Dutch roof allowed the removal of hot air from the first-floor level rooms.

The monitored room, which was the living room on the first-floor level, had bamboo woven partitions, a timber ceiling (at the first half of the room), and a bamboo woven ceiling (at the second half of the room), from which the roof ventilation was achieved by high air permeable ceilings and gable vents. The windows at the front of the dwelling consisted of timber-framed glass and louvre windows. The other windows consisted of timber-framed glass panels and timber panels. Portals were timber-panelled, double-leaved doors.

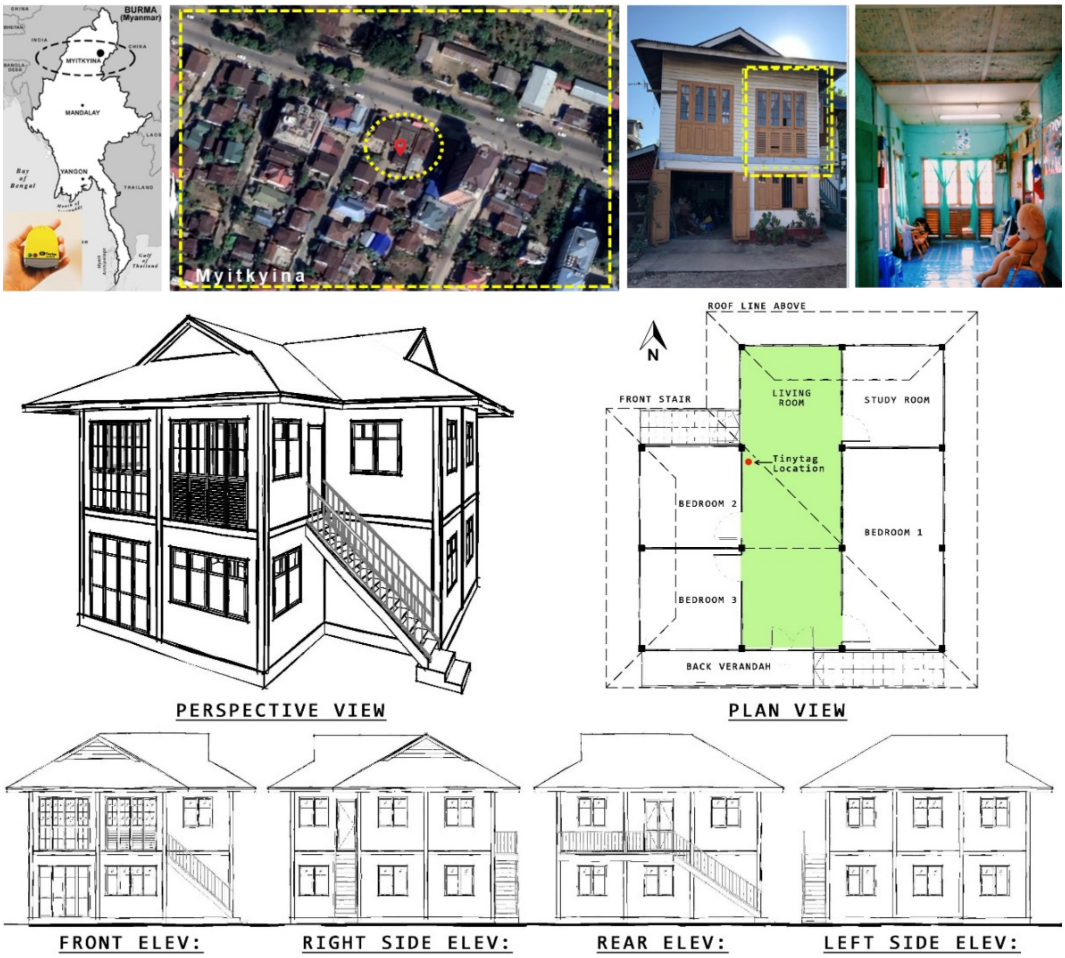


Figure 4-2. Location of the monitored dwelling in Myitkyina, instruments for measurement, location of a monitored room, and elevation views of the dwelling.

Monitoring processes: The indoor dry bulb temperature (DBT) and indoor relative humidity (RH) were continuously monitored from 01/01/2018 to 31/12/2018 at 30-minute intervals using a Tinytag *TGU-4500-Ultra-2* Gemini data logger. Tinytag data loggers are robust, reliable and cost-effective solutions to monitoring environmental conditions; therefore, they are commercially used in several warehouses for the pharmaceutical manufacturing process and in museums, archives and heritage sites to control the indoor thermal environment and energy-efficient chamber test (Fang et al., 2014, Huebner et al., 2018, Museums + Heritage Advisor, n.d). Several projects reported that Tinytag data loggers accurately monitor temperatures ranging from -25°C to +85°C and relative humidity from 0 to 95% (Gemini Dataloggers, 2017). The built-in sensor has a high reading accuracy; 32,000 reading capacity can be stored in the logger memory, so it is suitable to monitor continuously over a year, with 30-minute intervals.

Analysis method: Air temperature (AT), wet-bulb temperature (WBT) and heat index temperatures (HT) were utilised to analyse the data. The impacts of these parameters on the indoor thermal environment were discussed in Chapter-2. The dry-bulb temperature is a measure of air temperature which does not vary with the moisture content of the air. The wet-bulb temperature is widely used in the heat-stress index to assess health risks in physical work situations based on the heat-humidity threshold. The wet-bulb temperature equation used in this study was from an empirical inverse solution found to be valid for relative humidity between 5% and 99%, and air temperatures between -20°C and 50°C, except for situations having both low humidity and cold temperature (Stull, 2011). In order to analyse the heat stress risk through the humidity effect, the heat index temperature was calculated based on the heat index value obtained from the monitored data set and weather data, in which the relative humidity was factored in with air temperature (National Weather Service, 2019).

Long-term historical weather data and future climate data were and still are generally unavailable or limited in Myanmar. The typical and historical weather files used in this study were accepted as standard data for simulation for ASHRAE (Huang et al., 2014). The typical weather data set was created with data collected from 2003 to 2013. The future weather file was created for this study, which was based on the standard typical weather year, also used in Chapter 3. The future weather files used in this study were created by adding the predicted absolute monthly mean change value of the dry bulb temperature consistent with the reference weather files. The three seasons in Myanmar are affected by the monsoon onset time and withdrawal time; therefore, it was impossible to predict exact weeks and months for monthly mean change value. 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.

Simulation experiments: The simulations were performed using the Integrated Environmental Solution software (version 2019 Hotfix1) (IESVE, 2015). For the simulation experiments, a 'base case' model was first built in the IESVE simulation engine to represent the geometries, building function, and building envelope material properties of the monitored dwelling. The base case model had a low thermal capacity and insulation in walls and floors, and poor insulation and low solar absorptance value in the metal roof. The simulation model was calibrated using measured performance data and assessed against two error indexes: the Mean Bias Error (MBE) and the Root Mean Square Error (RMSE), following ASHRAE Guideline (ASHRAE, 2010, Gucyeter, 2018). The first index measures the consistency between the measured and simulated data, while the second index measures the deviation of the measured and simulated data. The formulae employed for MBE and RMSE are presented below, where '*n'* denotes the number of observations, '$T_{m,av}$' denotes the average of the monitored data for *n* observations, 'T_s' denotes the simulated data for '*n'* observations, and 'T_m' denotes the monitored data for '*n'* observations.

$$\text{MBE (\%)} = \frac{100}{T_{m,av}} \times \frac{\Sigma\,(T_s - T_m)}{n} \qquad \text{Eq - 4-1}$$

$$\text{RMSE (\%)} = \frac{100}{T_{m,av}} \text{ x } [\frac{1}{n} \times \Sigma\,(T_s - T_m)^2]^{0.5} \qquad \textit{Eq - 4-2}$$

Psychrometric analysis (Chapter 1, Figure 1-7) revealed that the use of high thermal mass could increase comfort percentage; therefore, a 'test case' model was introduced in the simulation experiment, in which the geometries and function of the dwelling were duplicated, but the building envelope material properties were switched to thick brick walls and concrete floors, for an increased degree of thermal capacity and insulation. Additionally, the modified base case and test case were added by changing the metal roof to a thatched one, to compare the differences between the impacts of vernacular and metal roof material in the present climates. A comparison of these four envelopes provides an in-depth understanding of their similarities and differences in terms of thermal performance for different climate conditions. Moreover, the four envelopes also manifest common material choices in Myanmar housing. Table 4-1 and Table 4-2 show the characteristics of the simulated dwelling, including material properties, occupant activities, internal gains, and window and door operation time.

Table 4-1. Material assumption of the monitored dwelling and simulations (CIBSE, 2015, IESVE, 2015)

Components	Description for Reference Vernacular Dwelling in Myitkyina	U Value, W/(m²K)	Thermal Capacity kJ/(m²K)	Solar Absorp-tance (α)
Base case (as per real-world conditions)				
Roof	Metal roof tile, gable vents with ceiling	2.7	4.0	0.2
Wall: Ground floor	4.5-inch walls with cement plaster and paint finish at both sides	1.7	83.0	0.3
Wall: Upper floor	Timber wall	3.0	15.6	0.3
Ground floor	Concrete slab with sand-filled below	0.8	174.7	-
Upper floor	Timber floor	2.0	15.6	-
Ceiling	Bamboo and timber ceiling	2.0	15.6	-
Windows	Opaque glazing windows with timber frame. Solar heat gain coefficient = 0.3; Visible transmittance = 0.8; U = 5.7.			
Doors	Timber door both for external and internal doors; U=2.2			
Infiltration	The rough assumption for air infiltration = 15 ach			
Test case				
Wall	13.5-inch walls with cement plaster and paint finish on both sides	1.1	117.0	0.3
Ground floor	Concrete slab, sand-filled below	0.8	174.7	-
Upper floor	Concrete slab	1.9	164.8	-
Others	Same as the base case			
Infiltration	Rough assumption for air infiltration = 1.5 ach			
Modified base case and test case				
Roof	Thatch roof tile, gable vents with ceiling	0.2	7.7	0.6
Others	Same as a base case			

In the monitored dwelling, the roof ventilation was achieved by high air permeable ceilings and gable vents. Therefore, the impacts of air permeability (particularly from the ceilings) on the indoor thermal environments were checked using simulation models. Air permeability (AP) is the physical property used to measure the airtightness of the building envelope; it is defined as air leakage rate per hour per square metre of envelope area at a test reference pressure differential across the building envelope of 50 Pascal. In this study, the monitored dwelling had high air infiltration, and the testing exercise was not able to be performed. Therefore, it was decided to check the impacts of a void area on the ceilings based on two different values. For which, AP20% represented a 20% void area on the ceiling surface, and AP5% represented a 5% void area on the ceiling surface for air permeability.

Table 4-2. Internal gains and schedules used in simulations

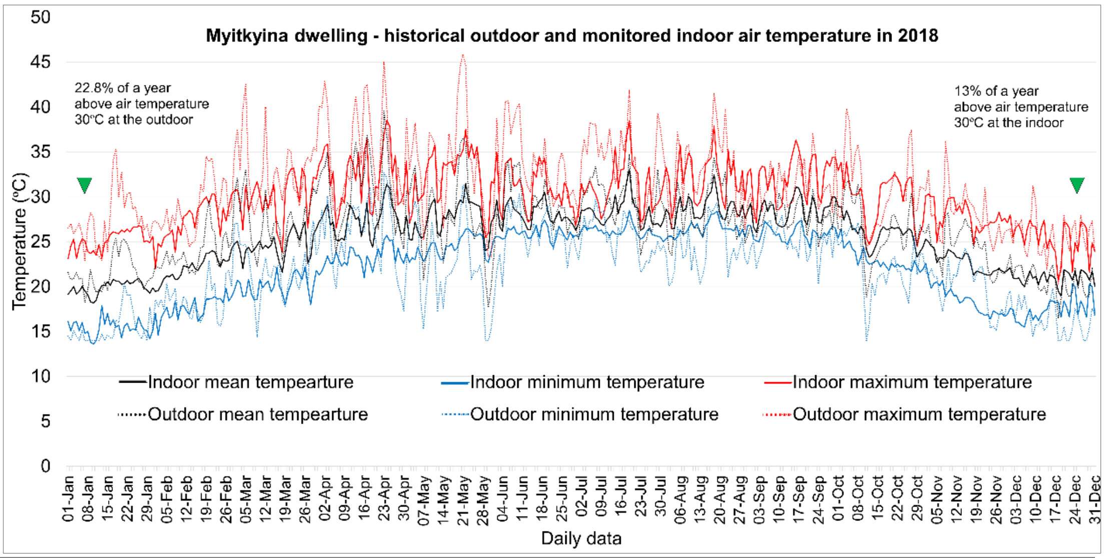
Assumption	Description	Operation / Schedules
Occupant activities	Three occupants (90 W/person for maximum sensible gain, 60 W/person for maximum latent gain)	06:00-09:00 am and 16:00-22:00 pm in living room; 22:00 pm to 06:00 am in bedrooms; 09:00 am - 16:00 pm in office
Internal gains	Lighting: 8 W/m^2 for sensible gain and 8 W/m^2 for maximum power consumption Equipment: 5 W/m^2 for sensible gain and 5 W/m^2 for maximum power consumption	Lighting: 18:00-22:00 pm Equipment: 24 hours
Window and door	Front windows (80% openable area) Side windows (80% openable area) Louvre windows (30% openable area) Doors (90% openable area)	Windows: 06:00 am - 22:00 pm Doors: closed continuously Louvres: opened continuously

4.2 Empirical data and simulation results

The results obtained from the monitored data sets and dynamic thermal simulations were summarised comparing differences in air temperatures, web-bulb temperatures and heat stresses, both for the monitored year 2018 and future climate scenario.

4.2.1 Air temperatures

The comparative analysis of the monitored indoor thermal environment data and the outdoor weather was presented using historical weather file data for the year 2018 and the typical weather file. As shown in Figure 4-3, small temperature differences between the indoor and outdoor indicated that the indoor thermal environment of the monitored dwelling had a close relation to the outdoor weather but maintained lower mean air temperature throughout the year. A comparison between outdoor weather data sets (Figure 4-4) revealed that the warmer hours above 30°C increased 1.8 times, and the warmer hours above 36°C increased 8 times in 2018, compared to the baseline typical weather year. Furthermore, the monthly outdoor temperatures above 36°C were significantly increased in the hot and wet season of 2018 (from April to August) compared to the typical weather year. A comparison between indoor and outdoor data sets for the year 2018 (Figure 4-4) revealed reductions in the monitored dwellings compared against the outdoor weather, including 9.8% fewer warmer hours above 30°C, and 12.5% fewer warmer hours above 36°C during the year.



	Annual hours above the temperature of 30°C	Annual hours above the temperature of 36°C
Outdoor weather data for the historical weather year 2018 (DBT)	22.8%	4%
Monitored indoor data for the historical weather year 2018 (air temperature)	13%	0.5%
Outdoor weather data for the typical weather year (DBT)	12.6%	0.5%

Figure 4-3. Historical outdoor dry bulb temperature and monitored indoor air temperatures in 2018, Myitkyina

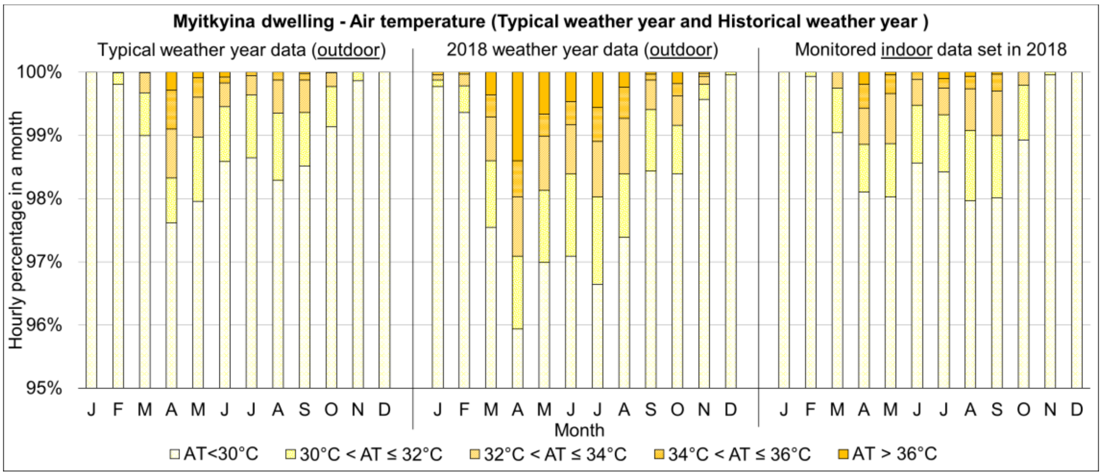


Figure 4-4. Monthly temperature range of the typical and historical year 2018 for outdoor air temperatures and monitored indoor air temperature of Myitkyina dwelling

4.2.2 Wet-bulb and heat index temperatures

A comparison of the monthly relative humidity for the typical weather year, the historical weather year 2018, and the monitored indoor data set revealed that the annual hours above the relative humidity of 90% decreased in 2018 compared to the typical weather year (Figure 4-5). The mean values of relative humidity in the typical weather year were higher than the historical weather year 2018 from January to May, and November to December (the hot and cold seasons, respectively). The hot and cold seasons were drier, but the hot and wet seasons were hotter in the year 2018 than the typical weather; therefore, their effect on wet-bulb temperature and heat index temperature was discernible.

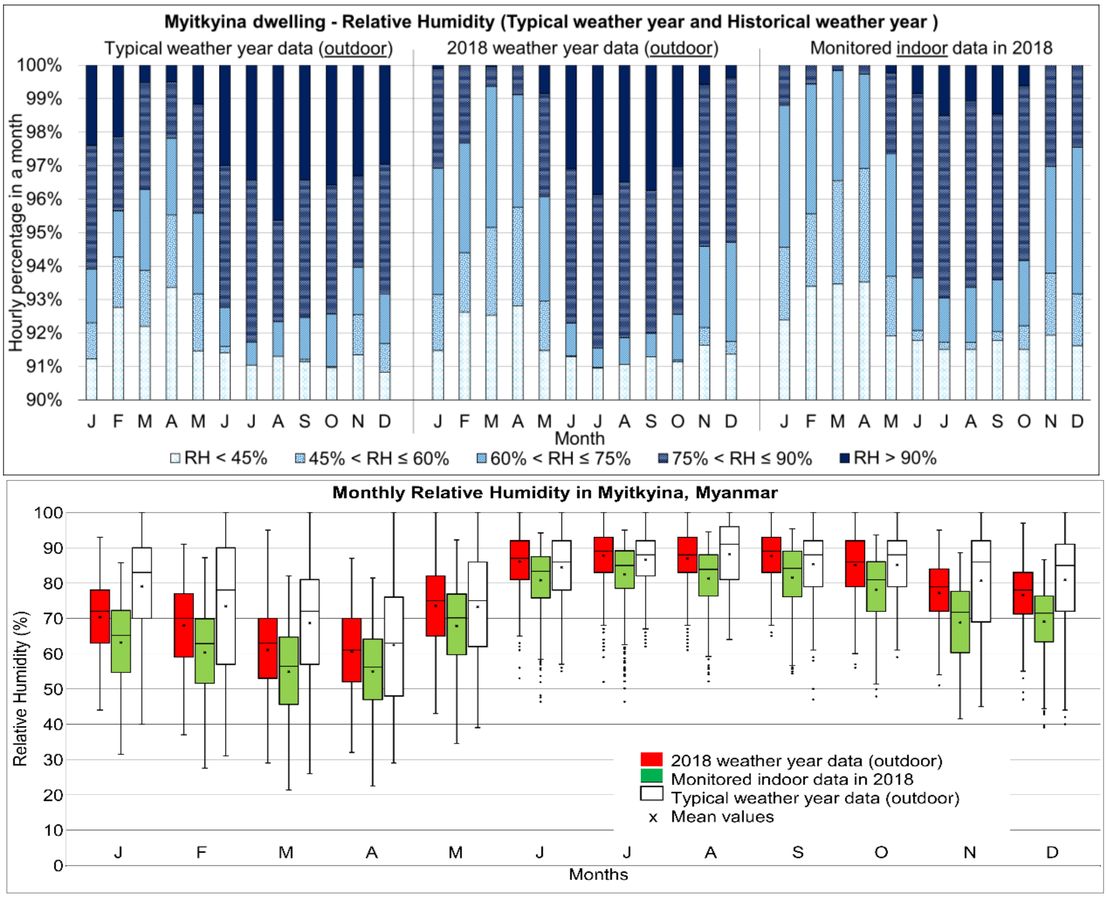


Figure 4-5. Monthly relative humidity from a typical weather year, the historical weather year 2018, and the monitored indoor data set of Myitkyina dwelling

The outdoor wet-bulb temperature above 30°C significantly increased from March to October and reached above 35°C from April to August in 2018, but the indoor wet-bulb temperature for 2018 and the typical weather year was below 30°C (Figure 4-6). The outdoor heat index temperatures for the year

2018 reached ‘an extreme danger’ stage from March to October, but the indoor heat index temperatures reached a ‘danger’ stage from June to September (Figure 4-7). Similarly, outdoor heat index temperatures for the typical weather year reached a ‘danger’ stage from May to October.

The proportion of wet-bulb and heat index temperatures for a year showed that the annual hours of wet-bulb temperatures below 20°C were 37%, 27.7% and 41.1% in the typical weather outdoor, historical weather outdoor for the year 2018 and monitored data set for the year 2018 (Figure 4-8). In the outdoor weather of 2018, a total of 8.3% (7.6+0.7) of the annual hours was above the wet-bulb temperature of 30°C, but the monitored dwelling maintained a total of 0.02% of the annual hours above the wet-bulb temperature of 30°C. The indoor monitored data set showed that 59.2% of the annual hours comprised a ‘no heat stress’ time, but 51.5% of the annual hours were found outdoors. Conversely, the typical weather file showed that 63.72% of the annual hours comprised ‘no heat stress’ time. There was no ‘extreme danger’ stage in the typical weather year and monitored indoor data set for the year 2018; however, 4.84% of the annual hours was found to be an ‘extreme danger’ stage in the historical outdoor weather in 2018.

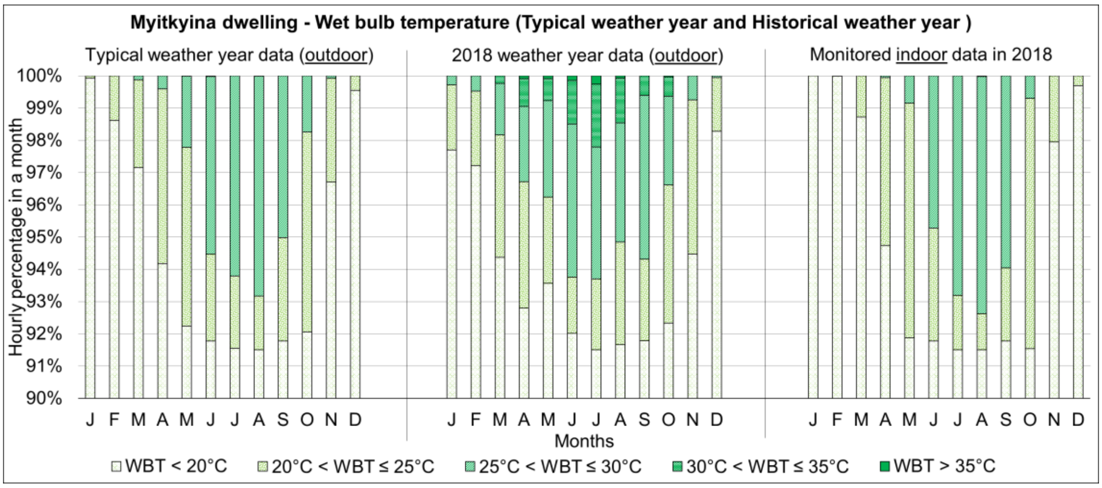


Figure 4-6. Monthly wet-bulb temperature range of the year in a typical and historical weather year data sets and monitored indoor data set, Myitkyina

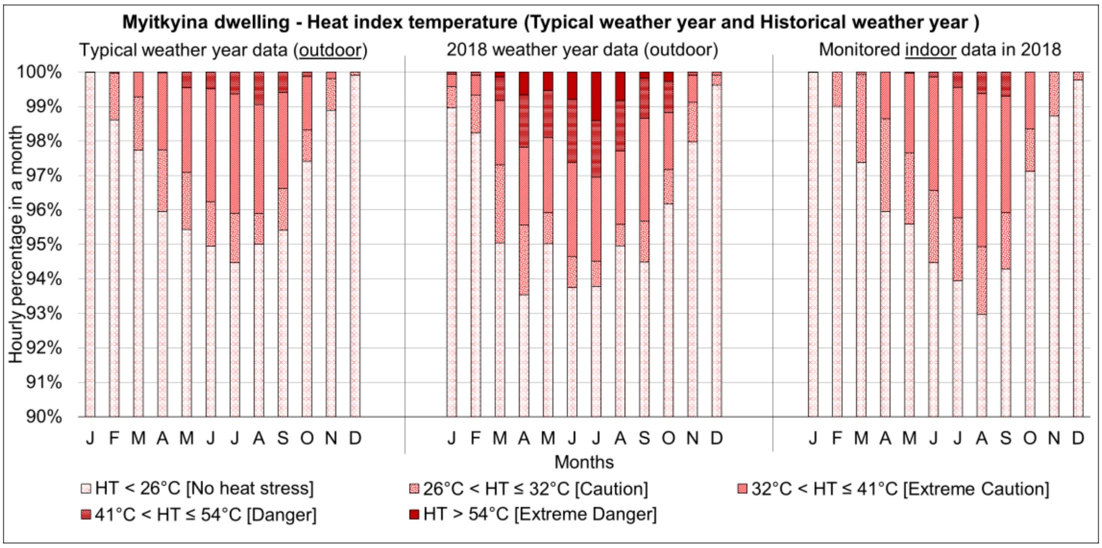


Figure 4-7. Monthly heat index temperature range of the year in a typical and historical weather year data sets and monitored indoor data sets, Myitkyina

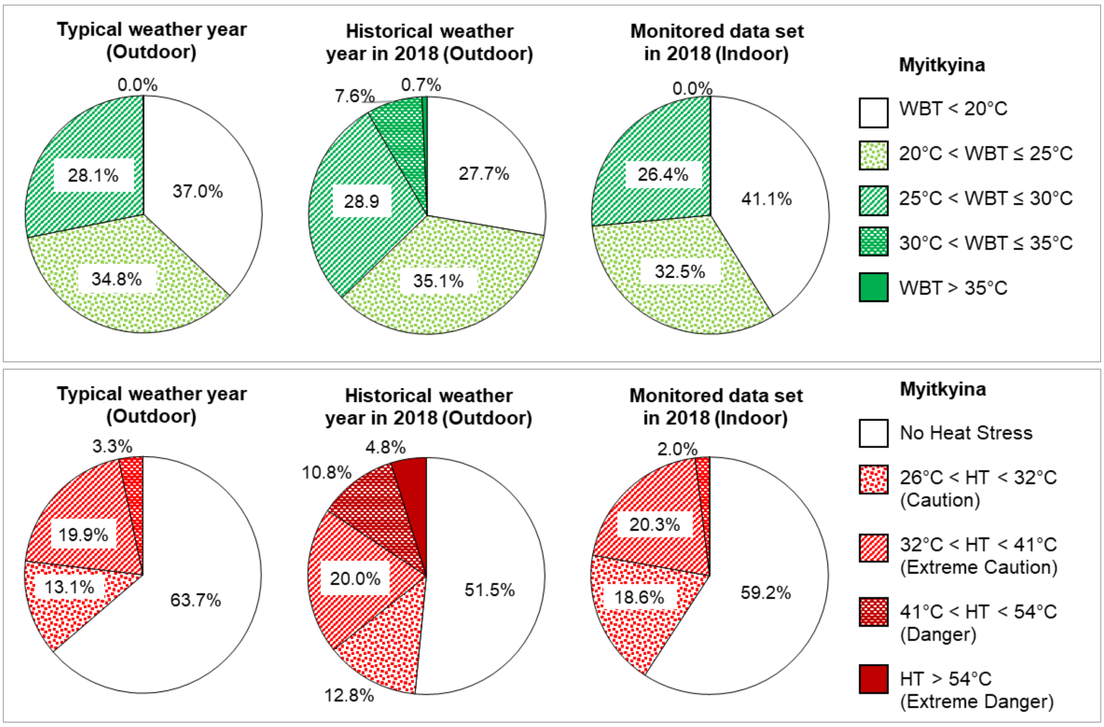


Figure 4-8. The proportion of heat index temperature and wet-bulb temperature in a typical and historical weather year data sets and monitored indoor data set, Myitkyina

In the monitored indoor data set, the highest air temperature of 34.5°C was found on the 23rd of April and the 18th of August (Figure 4-9). However, their heat index temperature on those days was significantly different due to a combined effect of air temperature and relative humidity. The heat index temperature reached 39.8ºC on the 23rd of April and reached 51.8ºC on the 18th of June. Although the relative humidity of December was as high as that of August, the heat index temperature of the 1st of December was as low as its air temperatures. The wet-bulb temperature reached 25.3ºC on the 23rd of April, 30.3ºC on the 18th of June, and 19.6ºC on the 1st of December.

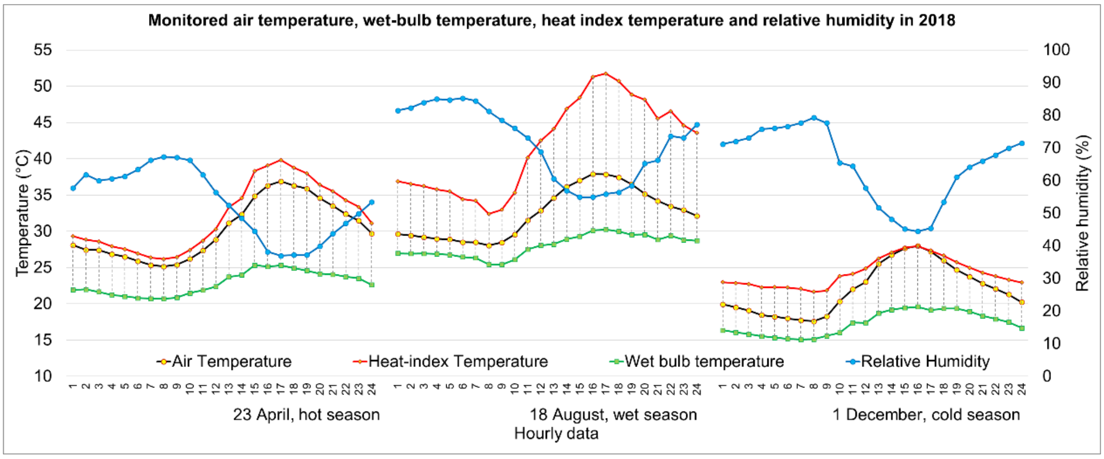


Figure 4-9. Monitored indoor hourly air temperature, wet-bulb temperature, heat index temperature and relative humidity in April, August, and December, Myitkyina

4.2.3 Simulation model validation

The regression and calibration plots of the monitored indoor data set and simulation model of the living room are shown in Figure 4-10 that revealed the indoor air temperatures of the monitored dwelling were slightly lower than the simulated model. It was found that the monthly MBE% of March and April were higher than their limits of 10% established by ASHRAE, but the other ten months were lower than ASHRAE limits. Likewise, the monthly RMSE% of March and April were higher than their limits of 30% established by ASHRAE. There was a small positive linear association between the simulated and measured data, with a correlation of 0.72 (R^2=0.52). This greater amount of unexplainable variation could be because the outdoor weather data for the simulated model was from the meteorological weather station; the assumption was made for the building envelope material properties and operating schedules of the simulated model; the latter could consist of human behaviours for the indoor thermal environment which was closely influenced by the weather outdoor.

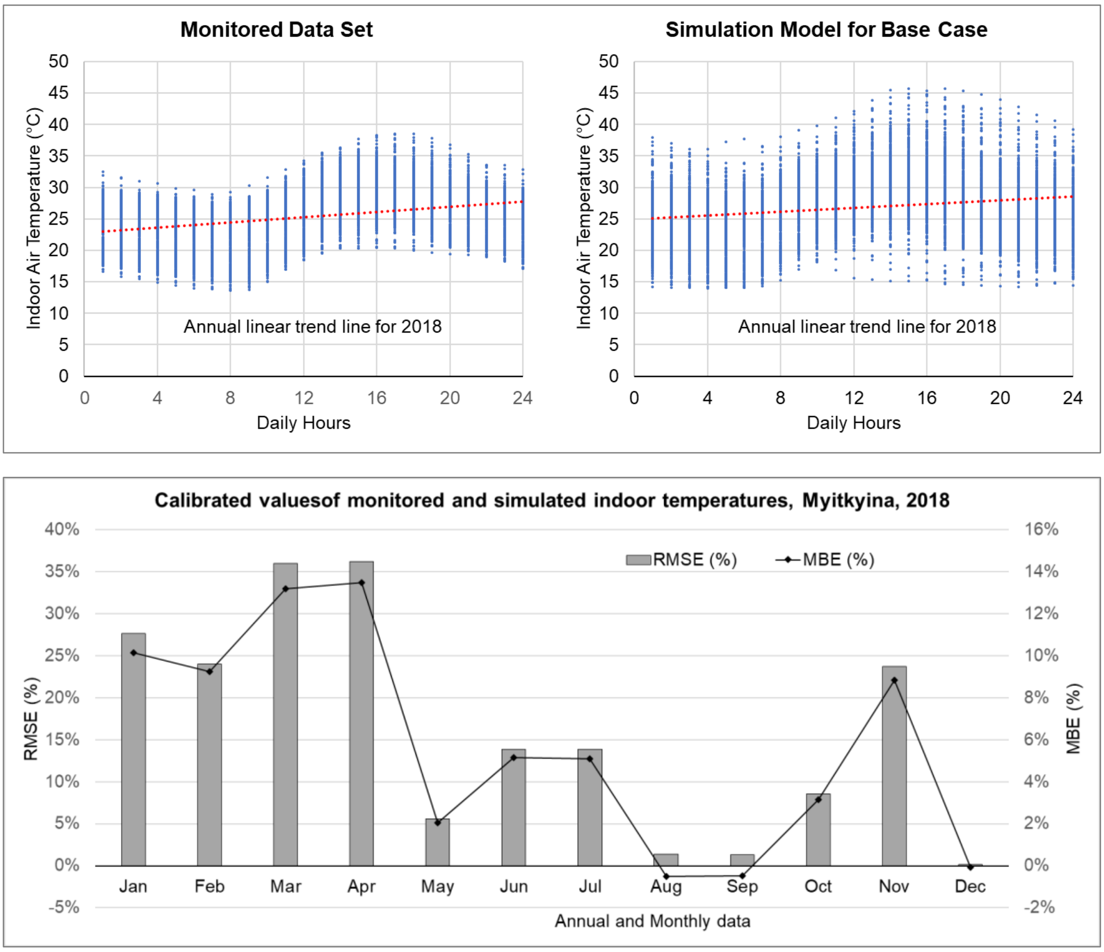


Figure 4-10. Regression and calibration plots of the monitored indoor data set and simulation model of the living room, Myitkyina

The 2018 annual and monthly outdoor and indoor temperatures from the monitored dwelling and simulated indoor temperatures of the different envelope scenarios were compared in Figure 4-11. Lower values for mean temperatures, upper quartiles, and upper whiskers were found in the monitored dwelling compared to the outdoor weather and simulated model. Due to a small positive linear association between the simulated and measured data, the annual mean temperature was 25.4ºC in the monitored indoor data set but 26.8ºC in the base case simulation model. Regarding the monthly variations, in the monitored indoor data set, the monthly mean value was 27.4°C in April, 28.7°C in August, and 21°C in December; the highest air temperature was 38.5°C in April, 37.9°C in August, and 28°C in December. In the base case simulation model, the monthly mean value was 31.1°C in April, 28.6°C in August, and 26.8°C in December; the highest air temperature was 45.7°C in April, 42°C in August, and 31.5°C in December.

In the box and whisker plots for annual temperatures (Figure 4-11), it was found that the indoor air temperatures of the base case and modified base case were only different two decimal values, and the indoor air temperatures of the test case and modified test case were only different one decimal values.

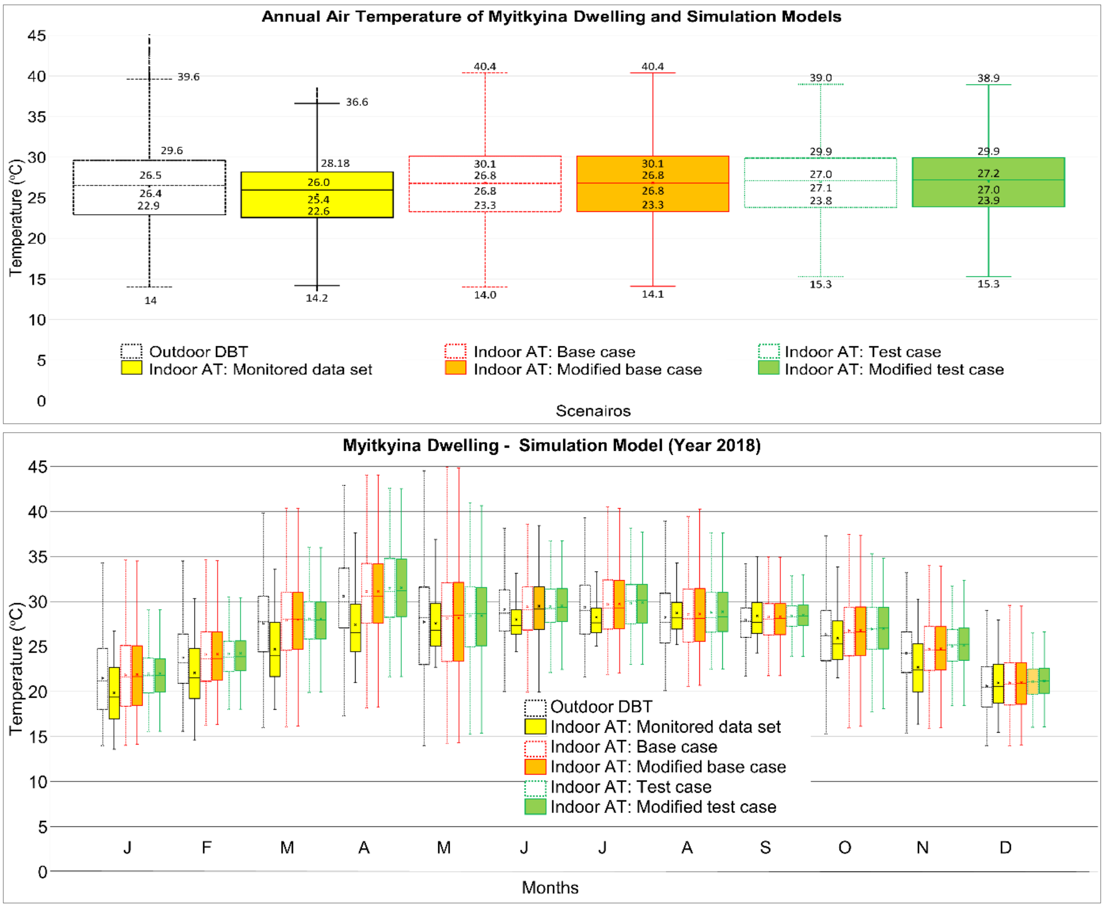


Figure 4-11. Annual and monthly air temperature from the historical weather year 2018, monitored indoor data set and simulation models of the living room, Myitkyina

Differences in air temperatures between the base case and test case simulation models were found in their monthly results rather than annual values. For instance, the annual mean temperature of the test case model (27.1ºC) was higher than the base case model (26.8ºC), but the highest air temperature of 40.4ºC was found in the base case model, while the test case model had 39ºC. When the roof material was changed from metal to thatch, a negligible temperature fall occurred (the test case and modified test case had a 0.1ºC temperature difference for their upper extreme). On the other hand, the test case and modified test case models maintained higher percentages of the annual hours above the air temperature of 30ºC but maintained a lower percentage of the annual hours above the air temperature of 36ºC than the base case and modified base case.

The impacts of air permeability on the indoor air temperature, which were achieved by the void area on the ceilings, were checked in Figure 4-12. It was found that the models with AP20% had a slightly lower percentage of the annual hours for indoor air temperatures above 30ºC than the models with AP5%. That showed highly permeable ceilings were desirable for the studied dwelling both for base and test cases.

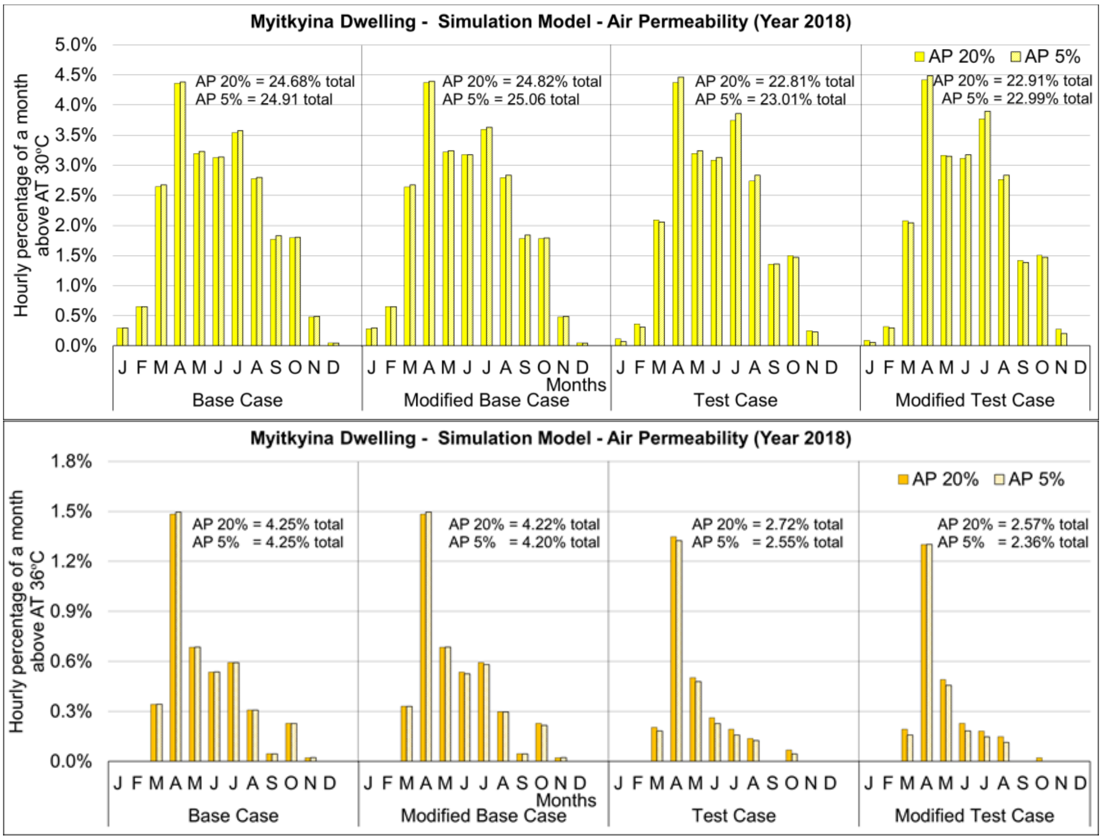


Figure 4-12. Monthly air temperature above 30ºC and 36ºC in two different air permeability conditions simulation models in 2018, Myitkyina

When the indoor air temperatures exceeded 36ºC, a noticeable reduction in the percentage of annual hours was found in both test case and modified test case simulation models, compared to the base case and modified case simulation models. That shows there was a more profound impact on the indoor thermal environments through the material properties of the building envelope than the air permeability achieved by the ceiling void.

4.2.4 Future climate scenario

This section presents the analysis of overheating risk and vulnerability to extreme events in the future for the selected building envelopes. Similar analyses were undertaken to compare the impacts of the four building envelopes on different weather scenarios, including the historical weather years 2016 and 2018, a typical weather year, and a future weather year. The future weather file was created by adding the predicted temperature increment based on the typical weather year. The results of the future weather year were found to have the same quartile length as the typical weather year, but the upper quartiles of all model scenarios above 30ºC in the future weather scenarios. The results of the box chart shown in Figure 4-13 indicated that the upper quartiles of all model scenarios were below 30ºC in the typical weather year and the historical weather years 2016 and 2018. However, the upper quartiles of all model scenarios were above 30°C in the future weather year, which means more than 25% of the annual hours in future weather year could be above 30°C. Consideration of extreme temperatures was not incorporated in the creation of the future weather file; therefore, the results of the annual hours above the air temperature of 36ºC for simulation models in the future climate scenarios were based on increased daily temperatures only.

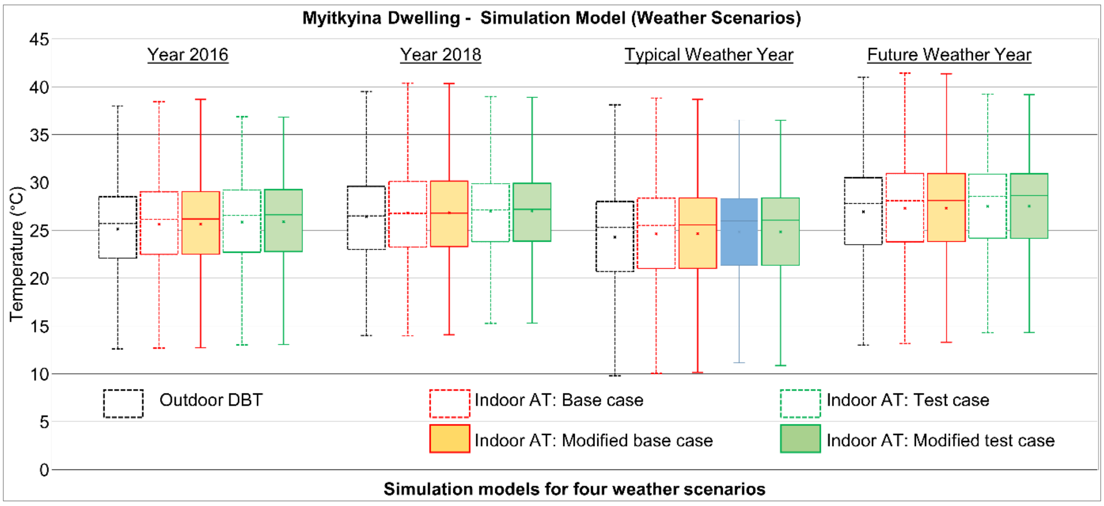


Figure 4-13. Simulated air temperatures of Myitkyina dwelling (living room) with four different building envelopes in different weather scenarios

Despite the exclusion of extreme events in the future weather file, as shown in Figure 4-14, the simulation results showed that 32.17%, 32.27%, 34.36% and 35.1% of annual hours with the air temperature above 30ºC were found in the base model, the modified base case model, the test case model, and the modified test case model, respectively. Likewise, 3.84%, 2.72%, 1.04% and 1.02% of annual hours with the air temperature above 36ºC were found in the base model, the modified base case model, the test case model, and the modified test case model, respectively. There was a 2.19% of the annual hour's increase in the amount of the year above the air temperature of 30ºC, but a 2.8% of the annual hour's reduction of time above the air temperature of 36ºC in the test case model compared to the base case model, due to building envelope material properties, particularly from the wall and floor.

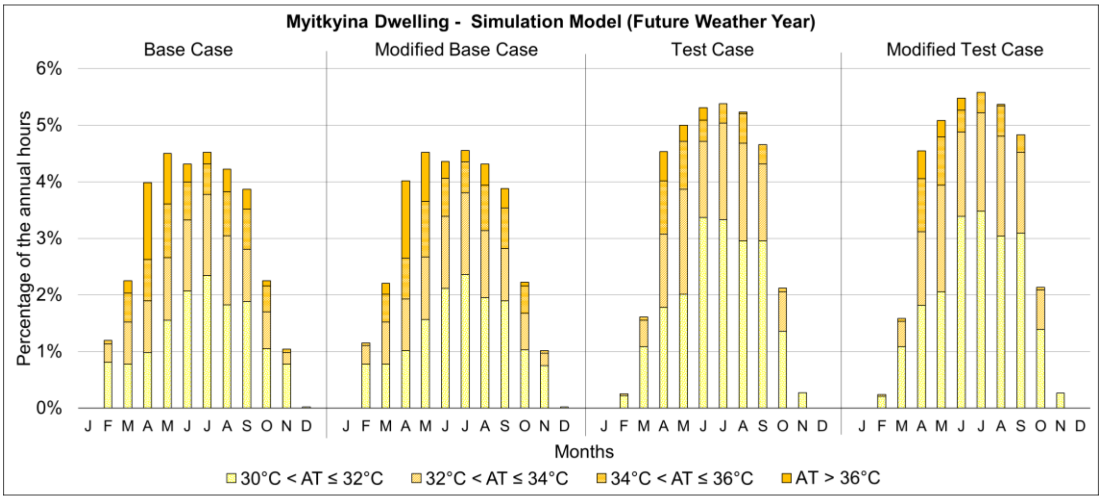


Figure 4-14. Monthly air temperature ranges of simulated dwelling (living room) with four different building envelopes in the future climate scenario

4.3 Discussion

Using a years' worth of monitored, empirical data with quantitative and analytical simulation experiments, the evidence-based results presented above are vital for a comprehensive knowledge of the local context and translating theory into practical applications. The findings observed from the monitored data set and the results of dynamic thermal simulations are discussed in the following sections.

4.3.1 Monitored dwelling in different weather scenarios

The monitored dwelling and simulation models were generated considering naturally ventilated conditions; therefore, the results of the indoor thermal environment were significantly influenced by the outdoor climates. Regarding the dry-bulb temperature for the outdoor condition, the warmer hours increased in 2018 compared to the baseline typical weather year, although there were no extreme heatwave events and considerable high temperatures in the monitored year of 2018; it should be remembered that particularly extreme highs are possible and probable, such as the 2010 heatwave in Myanmar (Nai, 2010). The frequency and intensity of high-temperature events for Myanmar are influenced by the occurrences of El Nino and La Nina events, which are seen more frequently than in 1972 over the world[39](Aung et al., 2017, p62). Further studies will need to address these concerns. On the other hand, the hot and cold seasons in the year 2018 were drier than in the typical weather year. Changes in outdoor dry bulb temperature and relative humidity could affect the health risk of the occupants in all free-running Myanmar dwellings due to their dependence on the heat-humidity threshold according to the outdoor weather.

Regarding the wet-bulb temperature for the outdoor condition, the historical outdoor weather of Myitkyina for the year 2018 showed that 7.6% of the annual hours had a wet-bulb temperature between 30°C to 35°C, and 0.7% of the annual hours had a wet-bulb temperature above 35°C. However, the monitored dwelling maintained indoor wet-bulb temperatures below 30°C. The outdoor wet-bulb temperatures rarely exceed 31°C worldwide (Salimi and Al-Ghamdi, 2020). Using the data based on the monthly average of daily maximum shaded wet-bulb globe temperature (in the warmest month) for the recent past (1986–2005), previous investigations (Andrews et al., 2018) highlighted that Myanmar is exposed to an extreme risk of heat stress with a 3°C increase. However, any rise above 35°C for prolonged periods will cause hyperthermia in humans, as metabolic heat dissipation becomes impossible (Salimi and Al-Ghamdi, 2020). That shows the emergence of heat and humidity is too severe for human tolerance in Myanmar; unquestionably, a

[39] During the period 1981-2010 there were several El Nino and La Nina events. For example, during 1997-1998 there was one of the strongest El Nino events recorded, and it was followed directly by a La Nina event in 1998-1999. El Nino years are linked to higher global temperatures and may also cause long durations of high maximum temperatures in Myanmar. In the years of El Nino, extreme weather events such as high temperatures were recorded in Myanmar. 2010 was another El Nino year. Twenty stations in Myanmar registered new maximum temperature records during April and May 2010. The years 2015-2016 are also influenced by a very strong El Nino (Aung et al., 2017, p62).

more in-depth investigation is required for the scope of building thermal comfort in Myanmar.

The indoor thermal environment of the monitored dwelling did not reach the ‘extreme danger’ stage in the year 2018, although 4.84% of the annual hours exceeded in the outdoor weather. As the heat index is a measure of how hot it feels when relative humidity is factored in with the actual air temperature, the quality of the indoor thermal environment depends on the combined effect of air temperature and relative humidity, the air exchange between the outdoor and indoor, and also how quickly humid, hot air is removed through ventilation. The results of the monitored indoor data set showed that the indoor thermal environments of the dwelling maintained lower temperatures and relative humidity than the weather year outdoor throughout the year due to the use of natural ventilation and building envelope material properties.

The monitored room contained several openings at the front, right, and back, and the opening time of the doors and windows could be varied by the occupants throughout the year, depending on the seasons. It is important to note that all simulation results contained general estimates of air infiltration and internal heat gains and a simplification of window and door opening time and occupant behaviour in terms of thermal comfort adaptation. Due to a small positive linear correlation, the discrepancies between the monitored indoor and simulated data sets were that the maximum outdoor dry bulb temperature reached above 45.1°C on the 23rd of April, the maximum indoor air temperatures reached above 36.9ºC in the monitored dwelling. And the maximum indoor air temperatures reached above 45.7ºC in the base case model (Figure 4-9)(Figure 4-11). That highlighted the importance of occupant behaviour for adaptive thermal comfort in the monitored dwelling. Note that adaptive thermal comfort methods employ the use of natural ventilation, while the heat balance method discourages it; moreover, people adapt to the temperatures within buildings, and they adapt the buildings themselves to suit their own thermal preferences (Roaf and Nicol, 2017). Besides these discrepancies, considerably, the base case simulation model had a reasonably good agreement with the monitored indoor data set.

4.3.2 Base case thermal envelope

The base case model contained a material assumption of the monitored dwelling, representing the use of vernacular materials such as timber walls and floors but poor roof insulation in the metal roof. In the box charts of the annual and monthly air temperatures (Figure 4-11), large temperature swings beyond the interquartile range (which means maximum and minimum temperatures) were found in the base case models compared to the test case models. The results presented here are in agreement with a previous study (Nicol et al., 2005): if buildings have poor insulation characteristics or are lightweight, with low thermal capacity, they are likely to produce uncomfortable indoor temperatures during hot summers; the results could be worse in the extremely high-temperature events.

In the tropics, the use of roof insulation and a ceiling with moderate insulation prevents intense solar heat gain. Strong similarities and a great variety of passive design in tropical vernacular architecture mechanisms, including the use of lightweight building envelopes, raised floors, and several openings, can be seen in vernacular construction in Costa Rica (Stagno, 2001), Indonesia (Stagno, 2001), Malaysia (Toe and Kubotab, 2015), Myanmar (Chapter 3), Thailand (Stagno, 2001), and Vietnam (Nguyen et al., 2011). However, the findings of this study showed that the use of vernacular building materials (i.e., timber walls) and customs in passive design techniques (i.e., metal roof with the ceiling, combined with roof ventilation) for building thermal comfort was insufficient to meet adequate indoor thermal comfort demand in the present and future climate scenarios. In Myanmar, the study in Section 3.1 showed that the use of ceiling is effective to protect from radiated heat gain from the metal roof above. In this work, the results also highlighted that the indoor thermal environment can be varied by the combined effect of air permeability through the ceiling and the material properties of the envelopes. From this respect, a potential strategy to improve the thermal performance of Myanmar vernacular housing to adapt to changing climate conditions need to be developed.

4.3.3 Test case thermal envelope

The test case thermal envelope consisted of the same roof material properties as the base case model, but the thermal capacities of walls and floors were 7.5 times higher than the base case model. Based on the findings of the psychrometric chart (Chapter 1, Figure 1-7), the test case envelopes were introduced using high mass for passive design strategies. Apart from the temperature ranges of the year profile (Figure 4-14), on the 23rd of April, the maximum indoor air temperatures reached above 42.54ºC in the test case model and 42.44ºC in the modified test case model against the maximum outdoor dry bulb temperature of 45.1°C at that time. The test case model was offset by 2.56°C against the maximum outdoor temperature, and the modified test case model offset the temperature of 2.66°C. Therefore, the results of this work showed that if buildings have some degree of thermal capacity in their walls, this will protect against extreme outdoor temperatures, particularly in the future climate scenario, but this is also likely to maintain a higher mean air temperature throughout the year.

Limitation: Using one-year monitored and simulated data sets, this study investigated whether vernacular dwellings in Myanmar can provide thermal comfort in the present and future climate, given vulnerability and overheating risks. Besides the limitation of the assumptions for the simulation exercises, it is necessary to note some limitations of this study.

In order to check the duration of the overheating for future climate, the adaptive comfort threshold is important. For instance, the current thermal comfort thresholds suggested by CIBSE Guide A is that temperatures should not exceed 28°C for more than 1% of occupied hours, with some variation for domestic spaces (CIBSE, 2015, CIBSE TM55, 2014). It was found that 26.64% of the annual hours were above the air temperature of 28°C in the indoor data set of the monitored dwelling in 2018 (13% of the annual hours was above the air temperature of 30°C). In identifying the overheating of free running, naturally ventilated buildings, the running mean outdoor temperature (T_{rm}) is essential in determining whether the acceptable maximum temperature exceeds 3% of occupied hours. T_{rm} values are calculated from α_{rm}, as a constant between 0 and 1, which defines the speed at which the running mean responds to the outdoor temperature. There has been a classic knowledge gap of unknown values for thermal neutrality for free-running buildings like the monitored dwelling. Furthermore, this study collected long-term measurements from the room, but there was a lack of correction for hot or cold surface temperatures to estimate the operative temperature of the room. The lack of operative temperatures and thermal neutrality values relate to the way in which overheating is defined, for which further studies are necessary.

Due to the limitation of the thermal comfort threshold, this study used the wet-bulb temperature and heat index equations to quantitatively check the heat stress from the combined effect of air temperatures and relative humidity. As the heat index equations were generated from a heat balance condition with a list of 20 fixed assumption factors, the results presented in this work were limited for an adaptive condition, as the monitored dwelling was in free-running mode. One should not forget that the airflow rate in the heat index equations was a fixed assumption; therefore, the heat index equation was not directly applicable to a free-running condition. The analysis undertaken in this work only aimed to calculate the degree of heat stress based on the humidity effect rather than the occupant's thermal comfort *per se*. Furthermore, in the simulations, boundary conditions, air infiltrations, internal gains, and occupant behaviours for door and window opening times were based on the assumptions; however, exact situations in real-world scenarios could be different. As suggested by previous studies (CIBSE, 2015, Rijal et al., 2011) and (Rijal et al., 2012), any simulation of the thermal behaviour of the building should include realistic algorithms for the occupant behaviour in relation to the use of windows and other adaptive behaviours, for which a realistic occupancy schedule is necessary to provide more robust, evidence-based finding.

Despite the limitations of this work, the findings of this study highlight the importance of envelope material properties and passive ventilation for building thermal performance and a substantial body of information for the recent weather year 2018 compared to the typical weather year.

4.4 Conclusion

Using empirical data sets and simulations, the building thermal performance study presented in this chapter offers the facts of an understanding of how the climate affected the performance of the observed dwelling. All results obtained from this work were generated from the living room of the monitored dwelling, which was from a single sample. A large monitoring data set including bedrooms is, therefore, necessary to identify what impacts climate change may have on Myanmar vernacular building.

Comparison between different weather data sets showed a 1.8 times increase in warmer hours above outdoor dry bulb temperature of 30°C, and an eightfold increase in warmer hours above the outdoor dry bulb temperature of 36°C in 2018 compared to the baseline typical weather year. In the indoor data set of the monitored dwelling in 2018, 26.64% of the annual hours was above the air temperature of 28°C, 13% of the annual hours was above the air temperature of 30°C, and 0.5% of the annual hours was above the air temperature of 36°C. Against the outdoor weather, the monitored dwelling maintained indoor wet-bulb temperature below 30°C and also showed the capability to maintain low heat index temperatures, below the 'extreme danger' stage, against the outdoor weather (which reached this stage for 4.84% of the annual hours). Therefore, it can be predicted that the monitored dwelling has some degree of thermal and ventilation performance to respond to the outdoor weather (with a 12.5% of the annual hour's reduction in yearly warmer hours above 36°C in the monitored dwelling against the outdoor weather). Nevertheless, the results presented in this chapter revealed that the emergence of heat and humidity is and will be too severe for human tolerance in Myanmar, for which the building thermal comfort of Myanmar dwellings need to be improved and addressed for climate adaptation.

The prediction for the simulation models for future climate scenario showed that the base case and modified base case would have a higher percentage of the annual hours above the air temperature of 36ºC than the test case and modified test case. Comparison between four envelopes showed a benefit of high thermal mass (test case) in protecting against extremely high temperatures, but at the expense of higher mean temperatures throughout the year. As the schedules of natural ventilation for openings were fixed in this work, further studies are necessary to investigate the combined effect of the use of high thermal mass and natural ventilation (especially the use of night-purge ventilation). This comparison (the base/test case and modified base/test case) provides to develop a study by introducing the Passivhaus building thermal envelopes parameters, thermal mass values and shading for the Myanmar climates; this consideration was addressed in Chapter 6.

Although the indoor thermal environment of the monitored dwelling maintained lower temperatures and relative humidity than the outdoor weather throughout the year, as it also had a close relation to the outdoor weather, a prediction can be made that the monitored dwelling (and similar vernacular houses in Myanmar) might face overheating risk and have high vulnerability to extreme events in the future due to the long-term climate risk index. Further studies are necessary to investigate applications to achieve greater thermal comfort for future climate scenarios.

Overall, this chapter provides a record of one-year empirical data set for two cities to enhance the reliability of findings from the simulation case studies (Zune et al., 2020b, 2020e) and contributes to valuable insights such as an understanding of the vulnerability of homes to overheating in Myanmar, particularly from the impact of climatic elements on thermal comfort, the impacts of changes in monsoon onset and withdrawal time, warmer night temperatures, and the urban heat island effect on the indoor thermal environment, and the impacts of different building envelope material properties (Zune et al., 2020b, 2020e).

Acknowledgements: The author gratefully acknowledges the homeowners of the monitored dwelling for their agreement to participate in this study and their facilitation of the field measurements.

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Nothing has

really happened

until it has been

recorded.

~Virginia Woolf (1882-1941)

from Virginia Woolf by Nigel Nicholson, p. I.

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5. Assessing Overheating Risk in Modern Dwelling through Empirical and Simulation Studies

Current climate change trends are expected to continue throughout the remainder of the 21st century and beyond. The long-term effects of climate change include increased frequency and intensity of droughts, heat-related events (e.g. heatwave and bush fires), changes in precipitation patterns, stronger storms, intense solar radiation, and lengthened frost-free seasons. Furthermore, on the global scale, the number of cold days and nights has decreased, and the number of warm days and nights has increased, based on observations between 1951 and 2010 (IPCC, 2014c). Different degrees of exposure to extreme climate significantly test the adaptability of buildings to perform in changing climate conditions (Roaf et al., 2005, p60). These adverse effects of climate change on buildings, both from sudden extreme weather events and from slowly changing climatic conditions, have profound impacts on the health, comfort, and quality of life of occupiers. Myanmar was ranked second out of 183 countries in the long-term climate risk index for the period 1990-2009 (Harmeling et al., 2011) and the period 1999-2018 (Eckstein et al., 2019). However, adapting buildings for climate change impact, particularly to extreme heatwave events, is still beyond the normal scope of what the built environment of Myanmar is prepared for.

Census results show that 70% of the population live in rural areas, and 30% live in urban areas in Myanmar as a whole. On the city level, 14% of the population live in the largest city Yangon, and 12% of the population live in the second-largest city Mandalay (Ministry of Labour, 2015). In Myanmar, high-rise buildings are mainly found in the old capital Yangon, and detached dwellings are found across the country. Modern dwellings, i.e., reinforced concrete structured dwelling which consists of brick walls, concrete floors and metal roof, are often found in most cities. The vast majority of housing in Myanmar is naturally ventilated, but the previous study (Chapter 3 and 4) revealed that the efficacy of this and other vernacular passive design techniques would not be sufficient to achieve thermal comfort in predicted future climate scenarios. Variations in weather caused by climate change, socio-political fluctuations that affect the availability of construction materials, and the rise of short-term solutions for thermal comfort through air-conditioning are increasingly prevalent in Myanmar. However, the impact of these on Myanmar housing had not been studied.

This was a gap in the current literature and, therefore, the focus of the chapter to assess the building thermal performance of a modern dwelling through empirical and simulation studies. For the case study presented in this chapter, the monitored dwelling was selected from a dense urban environment in Mandalay, which is also the last royal capital of Myanmar. Section 1.1.2 presents the characteristics of the city and its climate context. In this work, in order to close that knowledge gap by presenting:

- the analysis of an empirical data set collected in a typical home over one year, including microclimate data collected in an urban setting; and
- the analysis of a typical home modelled in dynamic simulation software and validated by the empirical data.

The simulations utilised existing weather data, the monitored weather data, and a morphed weather data representing future climate change scenarios. Building envelope materials and window shading were also varied in the model based on typical construction found locally in order to understand their role in the resultant building performance. The data sets were analysed in terms of the potential for heat stress using the heat index method. Like the vernacular dwelling study (Chapter 4), similar research approaches and steps (Figure 5-1) were proposed and applied in this study.

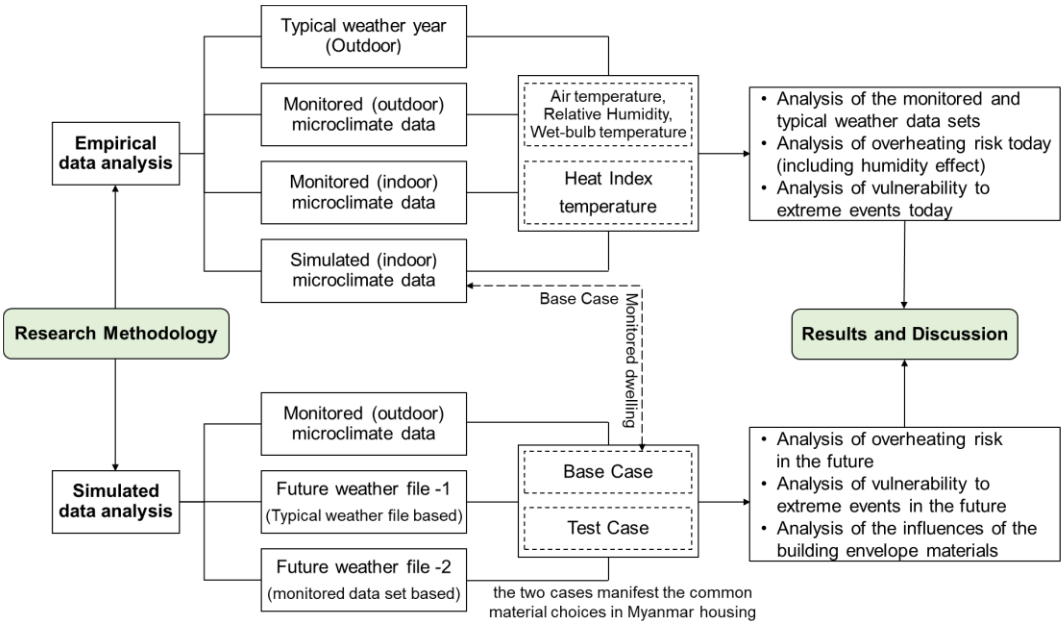


Figure 5-1. Research approaches and steps proposed and applied in this study

5.1 Methodology

In this study, how a modern dwelling responded to the present climate of Mandalay using monitored indoor and outdoor thermal environment data sets were investigated. Section 1.1.2 presents the characteristics of the city and its climate context. A comparison between the monitored data and the results of the simulation was undertaken in order to increase the confidence in the model, which was then used for thermal performance prediction of two different building envelopes. The impacts of changing climate conditions for two cases were discussed based on their results for a typical weather year, the monitored weather year 2019, and two future weather files generated for this work.

Monitoring processes: The monitored dwelling, shown in Figure 5-2 faced almost due north and was adjacent to similar detached masonry houses. The whole building covered an area of about 43.05 m^2, with a maximum length of 6.92 m and a maximum width of 6.22 m, and the total floor area was about 86.1 m^2.

Figure 5-2. Location of the monitored dwelling in Mandalay and instruments for measurement

The multi-purpose ground floor layout consisted of a living room at the front and an open concept kitchen and dining room at the back. There were two bedrooms on the upper floor. One big door at the front side of the ground floor served as an entrance and allowed for ventilation and daylight. Each bedroom had one window each and glass blocks that were aligned to the face of the front entrance door. High-level windows at the backside of the wall, shown in Figure 5-4, allowed cross-ventilation. The ventilation from all sides of the walls and the use of high vents can be seen in the selected dwelling. The dwelling had thicker walls (13.5 inches), and close assumptions for material properties of the dwelling were obtained from the owner. The dwelling was not selected at random, and rather it was conveniently selected due to the owner's familiarity with the subject (as an engineer), its location in a residential area, its fully residential function (as opposed to shophouses), and the availability of facilities for electricity and internet access throughout the year (in Myanmar, electricity and internet access is still limited, and services can be intermittently interrupted, even in the capital).

The monitoring work was conducted in the living room located on the ground floor, which was in free-running mode (Figure 5-3). The dwelling rarely had high activities while the measurements were undertaken; only three occupants used the house (early morning and evening in the living room, and night-time in the bedrooms). The windows and doors were frequently open from the morning to late evening (mainly for ventilation). As the space of the ground floor was an open layout, some internal gains occurred when the kitchen was used. All these activities and internal gains were considered in the simulations.

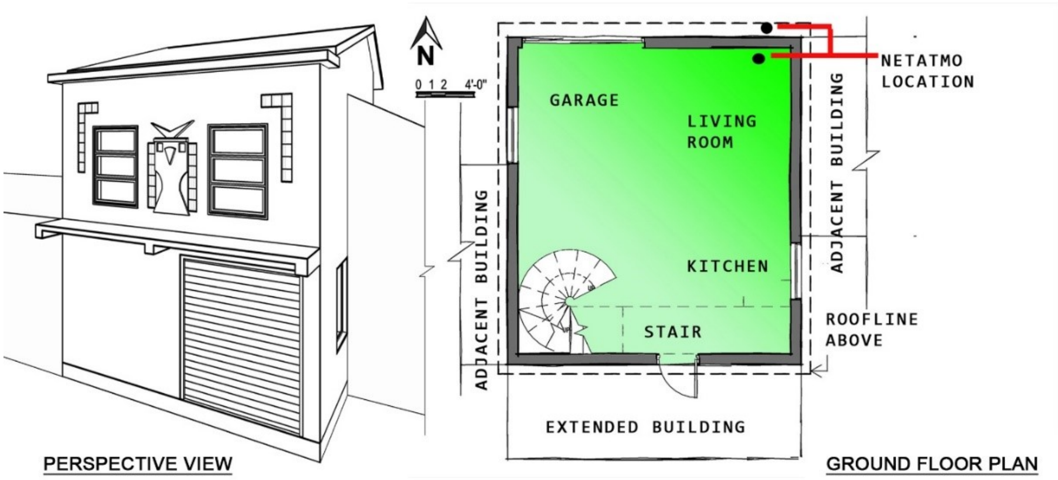


Figure 5-3. Monitored dwelling in Mandalay and location of a monitored room

The indoor and outdoor thermal environment data were continuously monitored from the 1st of January 2019 to the 31st of December 2019, at 30-minute intervals, using the Netatmo weather station and anemometer. Netatmo weather stations are commercially recognised for their user-friendly setting and reliable results; likewise, they are also used in academic research to monitor the local meteorological conditions (Le, 2020, Venter et al., 2020). The Netatmo is a prime example of the convenience of state-of-the-art technology that enables the user to remotely track real-time weather data in monitored environments (Netatmo, 2019). The weather station consists of two elegant aluminium units, one indoor and one outdoor sensor. The indoor module measures the indoor temperature, humidity, carbon dioxide level, noise, and air pressure through its sensors. The outdoor module measures the real-time weather data, such as temperature and relative humidity from the shaded place.

Although Chapman et al. (2017) have reported promising results of Netatmo with validation, the accuracy of the Netatmo monitored data is ±3%, which is challenging for a scientific study. Alternatively, several projects reported that the Tinytag data loggers accurately monitor temperatures ranging from -25°C to +85°C and relative humidity from 0 to 95% (Gemini Dataloggers, 2017). However, the Tinytag does not provide remote real-time tracking technology, and one needs to collect the monitored data when the memory card is full. Therefore, the Tinytag data logger was only used for four of the monitored months. The Netatmo indoor module and Tinytag were placed at the height of 1.2 m above the ground, and the Netatmo outdoor module was at the height of 1.5 m above the ground. The Netatmo anemometer was set 3 m above the top of the roof. The results of two monitored data sets from the Netatmo and Tinytag were able to validate each other although their hourly air temperatures, up to 0.8°C discrepancies. Both sets of data were used to compile a reliable set of monitored data.

Analysis methods: In this work, the temperature (AT), wet-bulb temperature (WBT) and heat index temperatures (HT) were utilised to analyse the data. The impacts of these parameters on the indoor thermal environment were discussed in Chapter-2 and 4. The monitored data set contained over a full one-year period for both outdoor and indoor microclimate data collected in an urban setting. From this, a weather file for the year 2019 was generated containing monitored outdoor DBT, outdoor RH, wind speed, and wind direction. The WBT, dew point, and atmospheric pressure were calculated according to the monitored parameters. Solar radiation and sky cover data were duplicated from the typical weather year file due to a lack of available data set.

UHI and variation between the urban and rural areas cause uncertainties in the building thermal performance design. The results of the Mandalay dwelling may not be representative of all dwellings in urban and rural areas of Myanmar because the temperature of an urban area can be significantly warmer than its surrounding rural areas, and the temperature intensity varies on a case-by-case basis. UHI and the impacts of adjacent buildings on the microclimate of the monitored dwelling were excluded from the simulations. The outdoor weather was monitored just outside of the dwelling in a highly urbanised area; thus, the results of small diurnal temperature swing between outdoor and indoor data sets could be due to UHI. Both external and internal temperature swings play a role to design the building envelope.

Two future weather files were created to investigate the thermal performance of monitored dwelling for future climate scenarios as summarised in Table 5-1. The future weather file-1 was based on the standard typical weather year from

ASHRAE, also used in Chapter 3. The future weather file-2 was based on the monitored year 2019. It is important to note that the diurnal temperature variations of the future weather file-2 were affected by UHI and global warming (increased mean air temperature and night temperatures) due to the database used for the monitored dwelling being located in the urban area of Mandalay. The predicted temperature increments were derived from the report "*Assessing the Climate Risks in Myanmar. A contribution to planning and decision-making in Myanmar: Technical Report*" (Horton et al., 2017) to create future weather files. The increased temperature values were predicted for 2041-2070 based on the baseline model of 1980 to 2006; therefore, the baseline years of the temperature increments and the reference weather files used in this study were different due to the constraints of available weather data sets. The future weather file creation method was referred to the use of a “shift” of a current hourly weather data parameter, following Jentsch et al. (2008). Future weather files used in this study were further limited due to their lack of unchanged parameters, as listed in Table 5-1.

Table 5-1. Weather files used in simulations

	Future weather file-1	Future weather file-2
Reference weather file	A typical weather year	Monitored weather year 2019
Modified parameter (the predicted increment is added to the reference weather files)	Dry bulb temperature from Table 1-1. 2.9ºC for the hot season (March to June) 2.4ºC in the wet season (July to October) 2.8ºC in the cold season (November to February)	
Unchanged parameters	Solar radiation, sky cover, relative humidity, wind, and precipitation	
Diurnal temperature variation	Large differences	Small differences
Urban heat island effect	Typical weather data from the airport	Monitored data from an urban dwelling

The future weather files used in this study were created by adding the predicted absolute monthly mean change value of the dry bulb temperature consistent with the reference weather files. The three seasons in Myanmar are affected by the monsoon onset time and withdrawal time; therefore, it was impossible to predict exact weeks and months for monthly mean change value. Consequently, it was assumed that each season has four months. 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.

Simulation experiments: The simulations were performed using the Integrated Environmental Solution software (version 2019 Hotfix1), which was also used in Chapters 3 and 4 (IESVE, 2015). The characteristics of the simulated dwelling, including occupant activities, internal gains, window and door operation time, and material properties, are shown in Table 5-3 and Table 5-4. In the simulation, the adjacent houses from the left, right and back of the monitored dwelling were also modelled; therefore, the external heat gains of the monitored dwelling were decreased due to the shading and sheltering of the adjacent houses. The elevation and section views are shown in Figure 5-4 display the front window (W1), windows from left and right sides (W2), windows at the top of the stair space (W3), front door (D1) and rear door (D2). Note that the practice of gable vent (roof windows) use in Myanmar vernacular architecture have been replaced by high-level window (W3) if the ceiling could seal the airflow.

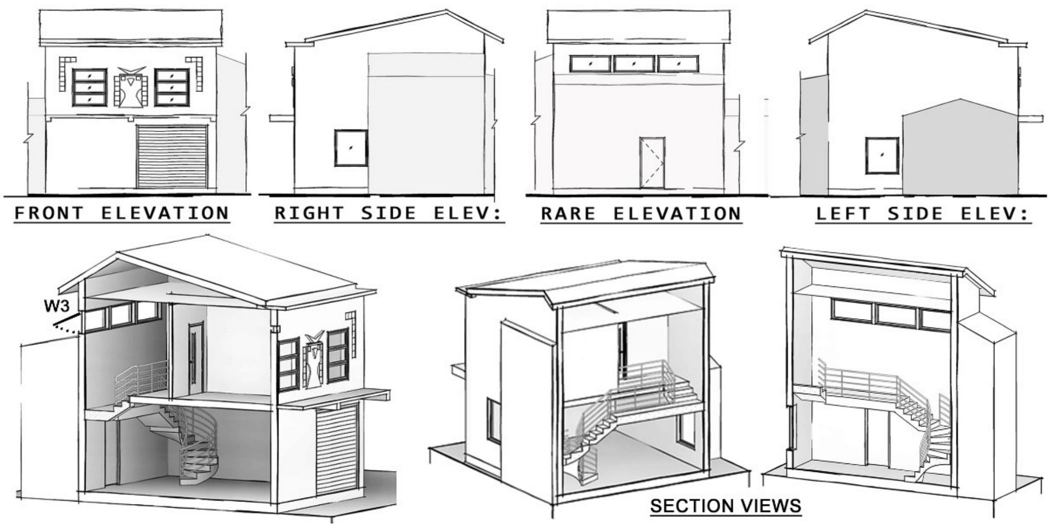


Figure 5-4. Elevations and section views of Mandalay dwelling

For the simulation experiments, a 'base case' model was first built in the IESVE simulation engine to represent the geometries, building function, and building envelope material properties of the monitored dwelling. The based model had some degree of thermal capacity and insulation in walls and floors, but poor insulation and less solar absorptance value in the roof. In the 'test-case model, the geometries and characteristics of the dwelling were duplicated, but the building envelope material properties were switched to vernacular materials, with a timber wall, timber floor, thatched roof, and high infiltration. The test-case model had a low thermal capacity and insulation in walls and floors, but high insulation and some degree of solar absorptance in the roof. The simulation model was calibrated using measured performance data and assessed against two error indexes: the Mean Bias Error (MBE) and the Root Mean Square Error (RMSE), following ASHRAE Guideline (ASHRAE, 2010, Gucyeter, 2018). The first index measures the consistency between the measured and simulated data, while the second index measures the deviation of the measured and simulated data. The formulae employed for MBE and RMSE are presented below, where '*n*' denotes the number of observations, '$T_{m,av}$' denotes the average of the monitored data for *n* observations, 'T_s' denotes the simulated data for '*n*' observations, and 'T_m' denotes the monitored data for '*n*' observations.

$$\text{MBE (\%)} = \frac{100}{T_{m,av}} \times \frac{\Sigma\,(T_s - T_m)}{n} \qquad \text{Eq - 5-1}$$

$$\text{RMSE (\%)} = \frac{100}{T_{m,av}} \text{ x } [\frac{1}{n} \times \Sigma\,(T_s - T_m)^2]^{0.5} \qquad \text{Eq - 5-2}$$

Table 5-2. Material assumption of the monitored dwelling (CIBSE, 2015, IESVE, 2015)

Components	Description for Reference Modern Dwelling in Mandalay	U Value, W/(m^2K)	Thermal Capacity (Cm), kJ/(m^2K)	Solar Absorptance (α)
Roof	Metal roof tile, roof void with ceiling	2.6778	4.0176	0.2
Wall	13.5 inches walls with cement plaster and paint finish at both sides	1.1378	117.00	0.3
Ground floor	Concrete slab with sand-filled below	0.7947	174.72	-
Upper floor	Concrete slab	2.3697	164.80	-
Doors	An aluminium door at the front, timber door at the back, timber door for internal doors			
Windows	Opaque glazing windows with aluminium frame. Solar heat gain coefficient = 0.292; Visible transmittance = 0.76; U = 6.0058.			
Infiltration	Rough assumption for air infiltration = 1.5 ach			

Table 5-3. Internal gains and schedules used in simulations

Assumption	Description	Operation / Schedules
Occupant activities	Three occupants (90 W/person for maximum sensible gain, 60 W/person for maximum latent gain)	06:00-09:00 am and 4:00-10:00 pm in living room 22:00 to 06:00 am in bedrooms
Internal gains	Lighting: 8 W/m^2 for sensible gain and 8 W/m^2 for maximum power consumption Equipment: 5 W/m^2 for sensible gain and 5 W/m^2 for maximum power consumption Cooking: 10 W/m^2 for sensible gain and 10 W/m^2 for maximum power consumption	Lighting: 18:00-22:00 pm Equipment: 24 hours Cooking: 06:00-08:00 am and 16:00-18:00 pm
Window and door	W1: 1.2 x 1.5 m (80% openable area) W2: 1.2 x 1.5 m (80% openable area) W3: 1.5 x 0.7 m x 3 Nos (60% openable area) D1: 2.6 x 2.6 m (90% openable area) D2: 0.9 x 2.1 m (90% openable area)	W1: Closed continuously W2: 06:00 am - 10:00 pm W3: Opened continuously D1 and D2: 06:00 am to 6:00 pm

Table 5-4. Material properties used in simulations, data set based on (CIBSE, 2015, IESVE, 2015)

Components		Description	U value	Cm	α
Test-case	Roof	Thatch roof, roof void and ceiling	0.2170	7.7	0.6
	Wall	Timber wall	3.0165	15.6	0.3
	Floor	Timber Floor	1.9977	15.6	-
	Others	Timber windows and timber doors			
	Infiltration	A rough assumption for air infiltration = 15 ach.			
Base-Case	Roof	Same as an assumption of the monitored dwelling			
	Wall				
	Floor				
	Others				
	Infiltration				

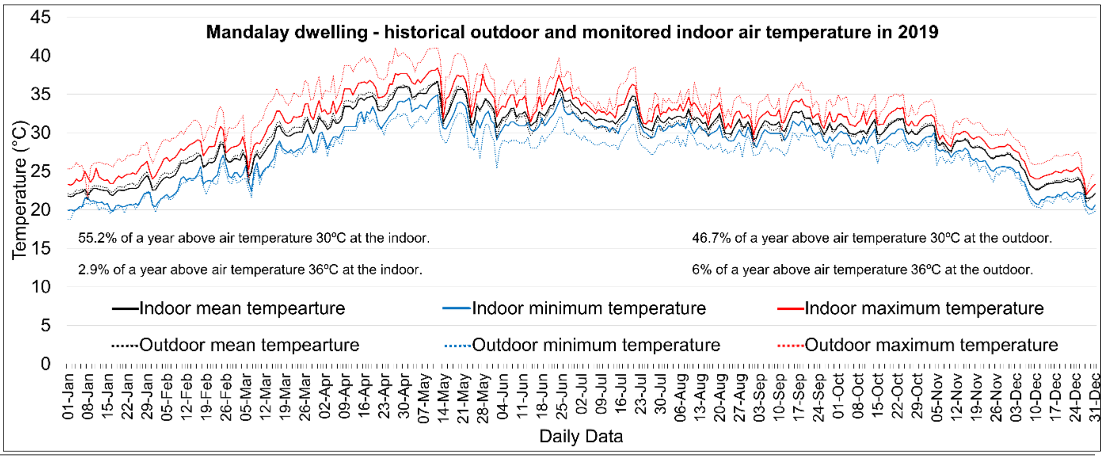
A comparison of these two cases provides an in-depth understanding of their similarities and differences in terms of thermal performance for different climate conditions. Moreover, the two cases also manifest common material choices in Myanmar housing. This comparison allowed reviewing which building envelope material plays a prevailing role for overheating in extreme events, strengths and weaknesses for future climate scenarios, and even potential retrofit approaches for changing climate conditions.

5.2 Empirical data and simulation results

This section presents the analysis of the monitored and typical weather data sets, the analysis of overheating risk (including humidity effect), and the analysis of vulnerability to extreme events today. The results were summarised by comparing differences in air temperatures, web-bulb temperatures and heat stresses, both for the monitored year 2019 and future climate scenario.

5.2.1 Air temperatures

Firstly, the air temperature differences between the monitored year and typical weather year were checked, from which changes in weather without the effect of the moisture of the air can be obtained. A comparison between the typical weather year and the monitored year revealed that the outdoor dry bulb temperature warmer hours above 30°C in 2019 doubled compared to its baseline typical weather year from 2005 to 2013, and also warmer hours above 36°C were significantly increased in 2019 (Figure 5-5 and Figure 5-6). Furthermore, the comparison for monthly temperature range showed that the time for outdoor DBT below 30°C was decreased (means DBT above 30°C were increased) in the monitored year 2019 compared to the typical weather year (Figure 5-6).



	Annual hours above the temperature of 30°C	Annual hours above the temperature of 36°C
Monitored outdoor data for the historical weather year 2019 (dry-bulb temperature)	46.7%	6%
Monitored indoor data for the historical weather year 2019 (air temperature)	55.2%	2.9%
Outdoor weather data for the typical weather year (dry-bulb temperature)	28.44%	0.4%

Figure 5-5. Monitored outdoor dry bulb temperature and indoor air temperatures in 2019, Mandalay dwelling

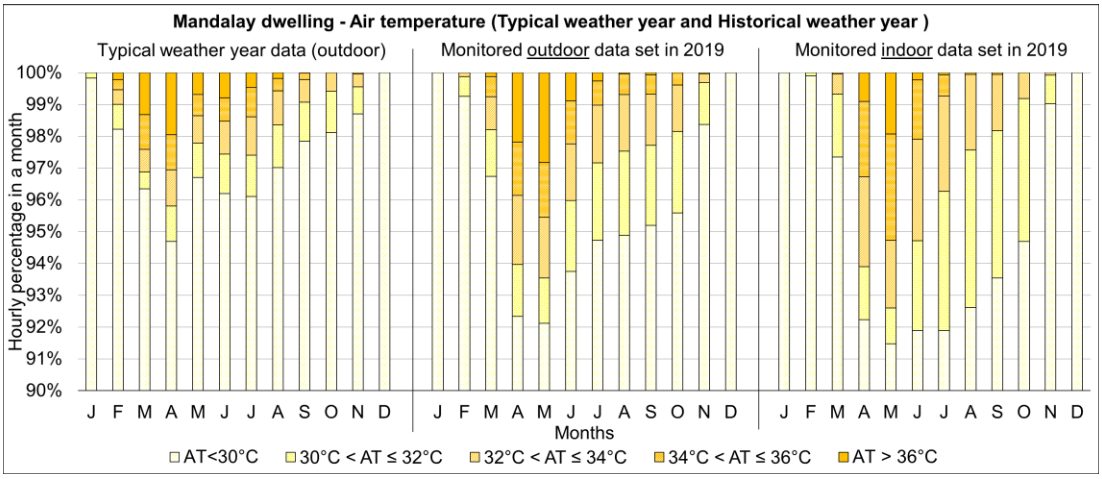


Figure 5-6. Monthly temperature range of the typical and monitored year 2019 for outdoor air temperatures and monitored indoor air temperature of Mandalay dwelling

5.2.2 Wet-bulb and heat index temperatures

Wet-bulb temperature is widely used in the heat-stress index, and heat stress for HT can be measured based on the heat index value, in which the RH is factored in with AT. Therefore, firstly, the monthly RH was checked in Figure 5-7 for the typical weather year, the monitored weather year 2019 and the monitored indoor data set of Mandalay dwelling. Monthly RH results showed that RH above 75% in the typical weather year was higher than the historical weather year 2019 throughout a year. The percentage of the annual hour above RH 75% was decreased in the year 2019 compared to the typical weather year. The RH in 2019 rarely reached 90% humidity.

Although the year 2019 was drier than the baseline typical weather year, the effects of RH on WBT and HT were found due to increased AT. Furthermore, different ranges of high WBT and HT were found once the monsoon onset time had started. In Figure 5-8, the outdoor WBT above 25°C were significantly increased from April to November due to increased monthly temperatures in 2019. Similar results were found in the 2019 indoor data set. To note that the DBT above 30°C was increased in 2019, but the RH above 75% were decreased. Therefore, both the WBT and HT were increased in 2019. It also showed that the percentages of the annual hours in a month for a high HT were higher in 2019 compared to the typical weather year. In 2019, the HT reached ‘a danger stage’ from April to October in the outdoor data set and “an extreme caution stage” from May to October in the indoor data set.

Figure 5-9 presents the proportion of WBT and HT for a year. The typical weather year maintained 31.7% of the annual hour for the WBT above 25°C, and 5.49% of the annual hour, reaching the 'danger' heat stress levels. In the outdoor weather of the year 2019, a total of 51% of the annual hour was above WBT 25°C, and there were 14.06% of the annual hour reaching 'danger' heat stress levels. The indoor monitored data set showed that 48,5% of the annual hour 2019 was above WBT 25°C, and there were 4.65% of the annual hour with a 'danger' stage heat stress condition.

The proportion of WBT below 20°C was decreased in the year 2019 compared to the typical weather year. The proportion of the 'no heat stress' stage was decreased in the year 2019 compared to the typical weather year. For the outdoor condition, there were 43.53% of the annual hour with 'no heat stress' stage in the typical weather year, but there were only 23.72% of the annual hour with 'no heat stress stage' in the year 2019. Therefore, the proportion of the 'no heat stress' stage for the indoor condition in 2019 was also decreased.

Comparisons between yearly and monthly results of the monitored and typical weather data sets showed that there were increments in WBT and HT. Therefore, their intensity on the peak days of each season in 2019 was checked in Figure 5-10. In the monitored indoor data set, the highest AT of 38.4°C was found on the 12th of May, and 33.9°C was found on the 11th of August. However, their HT on those days was similar different due to a combined effect of AT and RH. The HT reached 44.83ºC on the 12th of May and also reached 43.63ºC on the 11th of August. As the RH of December was not as high as August, the HT of the 1st of December was 29.78ºC on the 1st of December. The WBT reached 27.51ºC on the 12th of May, 28.2ºC on the 11th of August and 22.31ºC on the 1st of December. Significant differences between the outdoor and indoor RH were found; therefore, the combined effect of hourly AT and RH were caused by differences between the weather outdoor and indoor thermal environment.

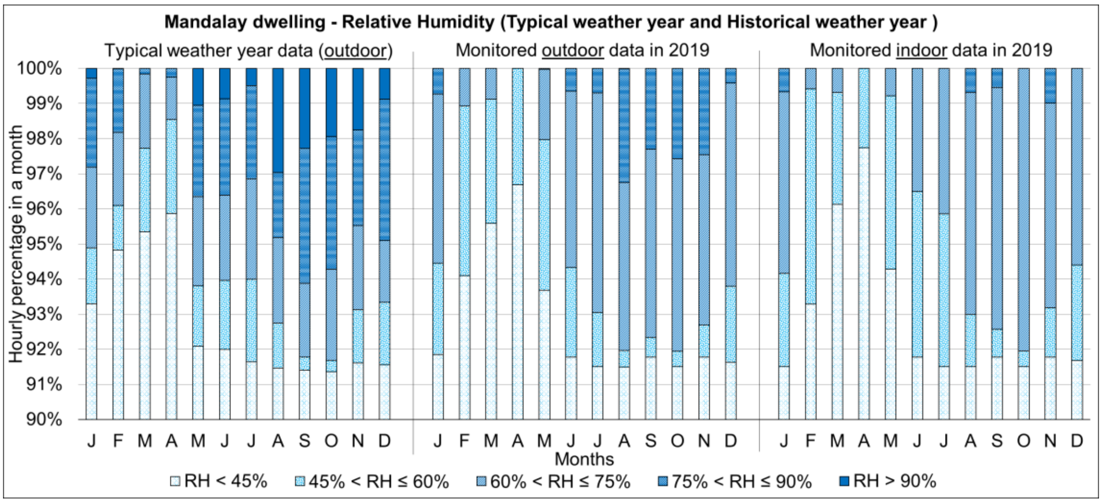


Figure 5-7. Monthly relative humidity from a typical weather year for outdoor and a monitored weather year 2019 for indoor and outdoor for Mandalay dwelling

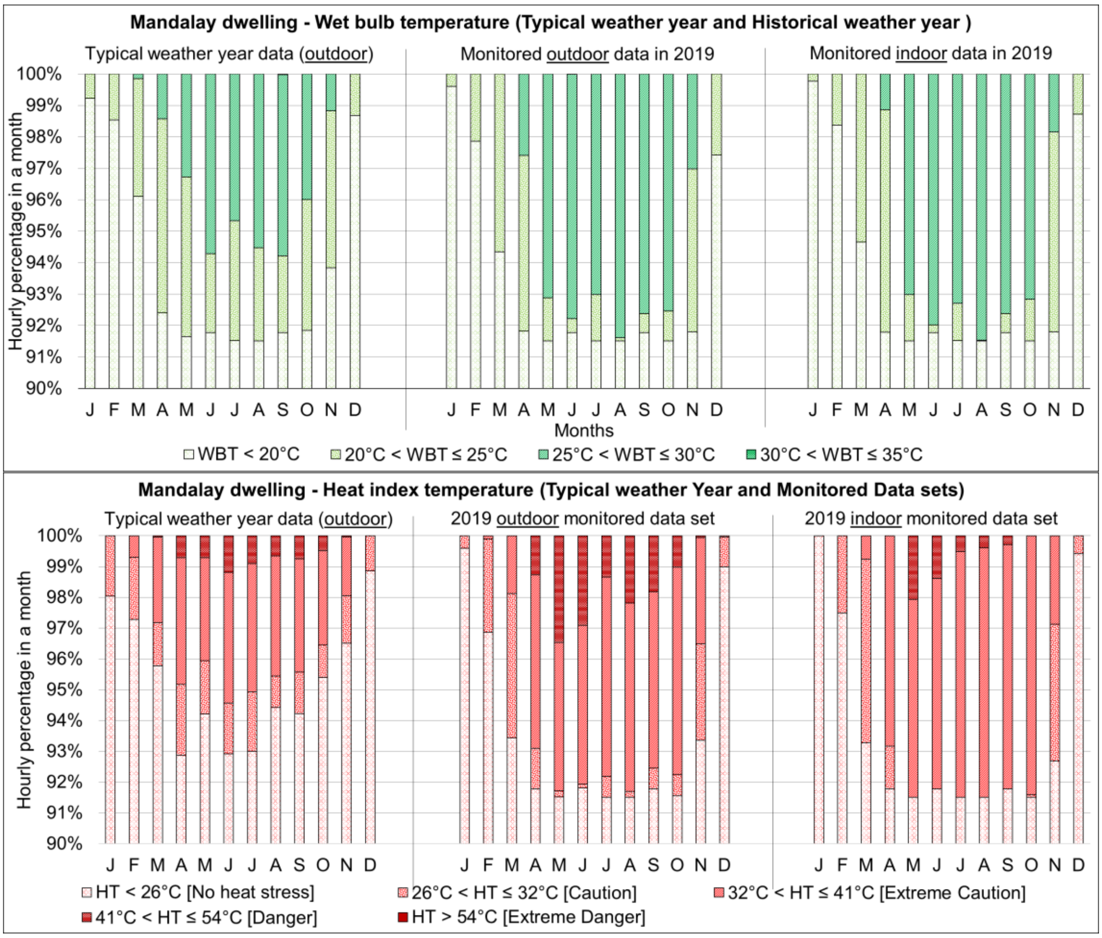


Figure 5-8. Monthly wet-bulb and heat index temperatures range of a year in a typical and monitored weather year data sets, Mandalay dwelling

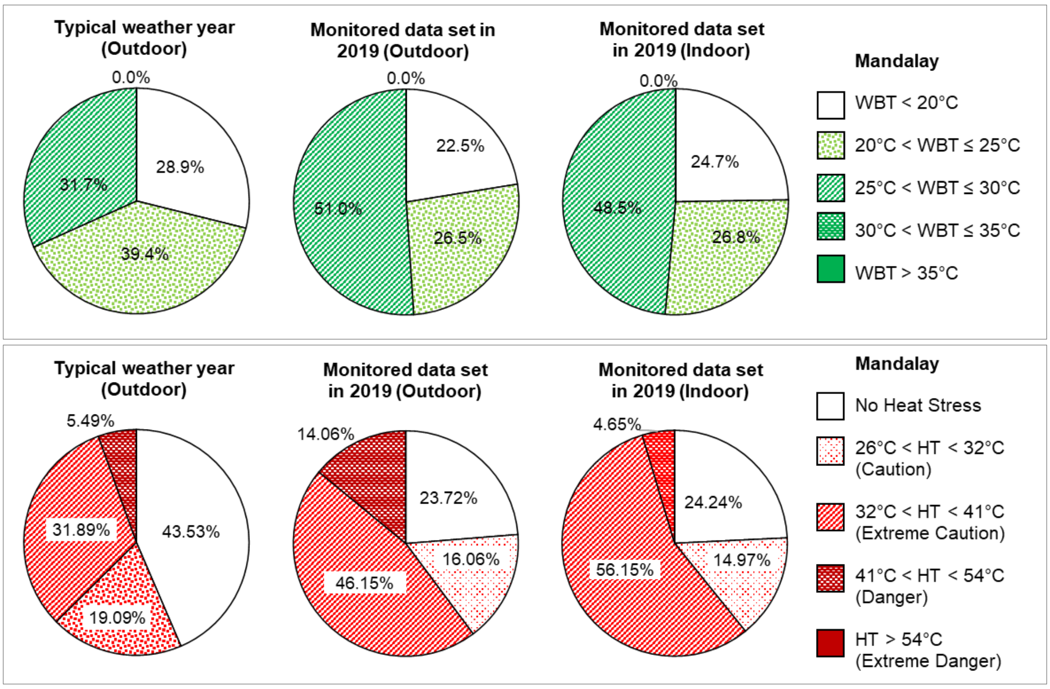


Figure 5-9. The proportion of heat index temperature and wet-bulb temperature in a typical and monitored weather year data sets, Mandalay dwelling

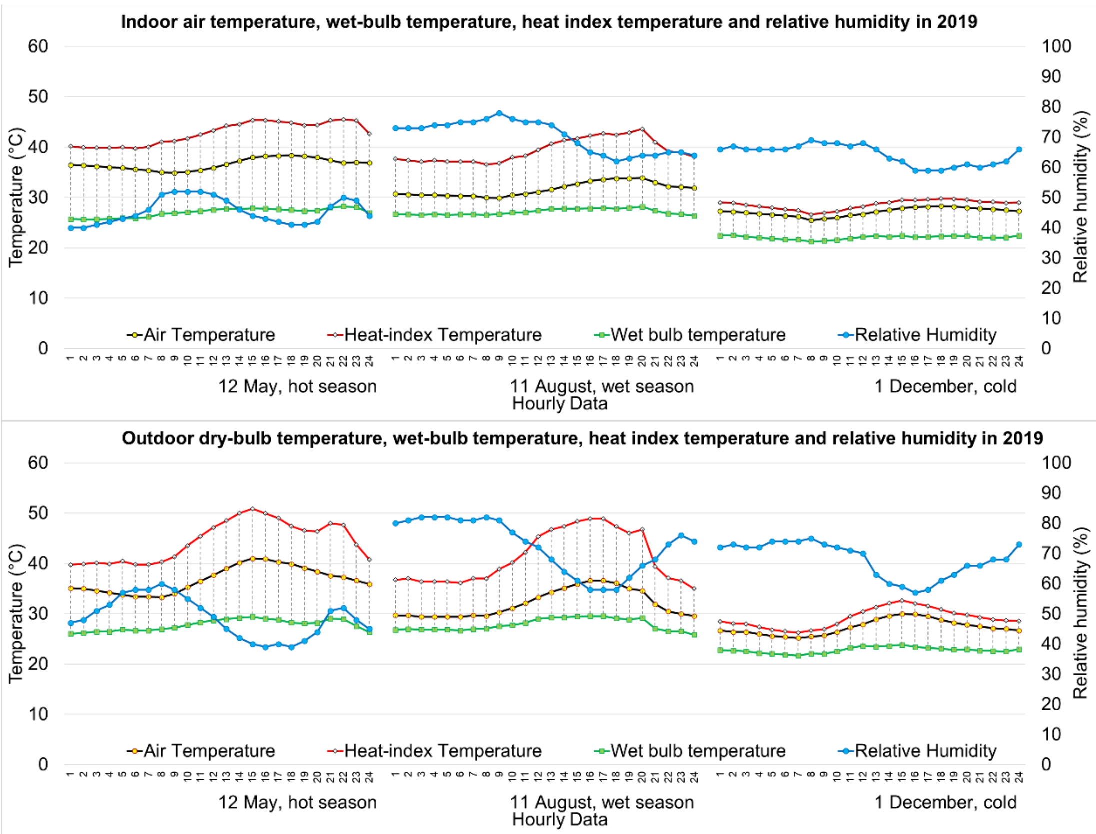


Figure 5-10. Monitored indoor and outdoor hourly temperature, wet-bulb temperature, heat index temperature and relative humidity on 12 May, 11 August and 1 December in 2019, Mandalay dwelling

5.2.3 Simulation model validation

A regression plot of the monitored indoor and outdoor data sets and simulation indoor data set is shown in Figure 5-11, which revealed the indoor air temperatures of the monitored dwelling were slightly lower than the outdoor and the simulated model. The Mean Bias Error (MBE) and Root Mean Square Error (RMSE) were calculated to be 0.2% and 15.2% between measured and simulated data, very lower than their limits of 10% and 30% established by ASHRAE, respectively. This showed a large positive linear association between the simulated and measured data sets, with a strong correlation of 0.95. Note that the assumption was made for the building envelope material properties and operating schedules of the simulated model.

The monsoon onset and withdrawal time can be tracked by checking the monthly AT and RH changes (Figure 5-12). In the typical weather year, when the monsoon onset time came in May, the monthly AT was dropped, but the RH was increased. In 2019, the monsoon onset time came late; therefore, the marked changes in monthly AT and RH were found in June. When the monsoon arrived, the lower extreme of DBT dropped about 20°C in the typical weather year but was maintained above 25°C in the monitored year 2019. The upper and lower extremes of DBT were greater in the typical weather year than the monitored year 2019. Shorter lengths of upper quartile and lower quartile throughout the year were found in the monitored outdoor and indoor data sets, and their monthly median values were also higher than the typical weather year. The results of monthly median values and length of quartiles revealed that the annual and monthly mean temperatures were increased in the monitored year 2019 compared to the typical weather year. Moreover, the values of annual and monthly mean RH were dropped in the monitored year. Overall, the monitored year 2019 was drier and warmer than the typical weather year and had a smaller diurnal temperature swing.

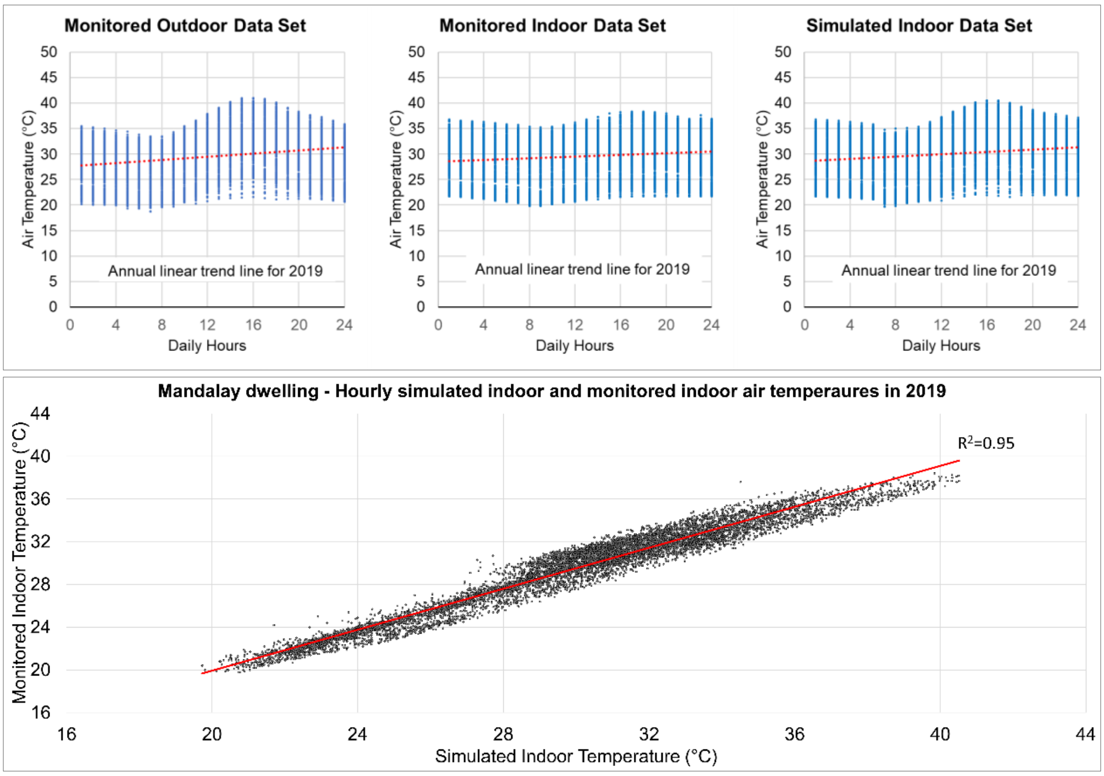


Figure 5-11. A regression plot of the monitored indoor and outdoor data sets and simulation indoor data set for the living room, Mandalay

The discrepancies in AT between the monitored indoor data set and the results of the based simulation model were noticeable. For instance, in April, in the monitored indoor data set, the monthly median value was 28.8°C and the highest AT was 34.2°C. On the other hand, in April, the monthly median value was 29.8°C, and the highest AT was 36.5°C in the simulation model. It was also found that the discrepancy in the RH between the simulation model and monitored data sets were even more obvious, especially from June to December. Change in heat store in a building results in a combination of solar heat gain, ventilation heat gains or loss, evaporative heat loss, internal heat gains and conduction heat gain or loss (Szokolay, 2008, p35).

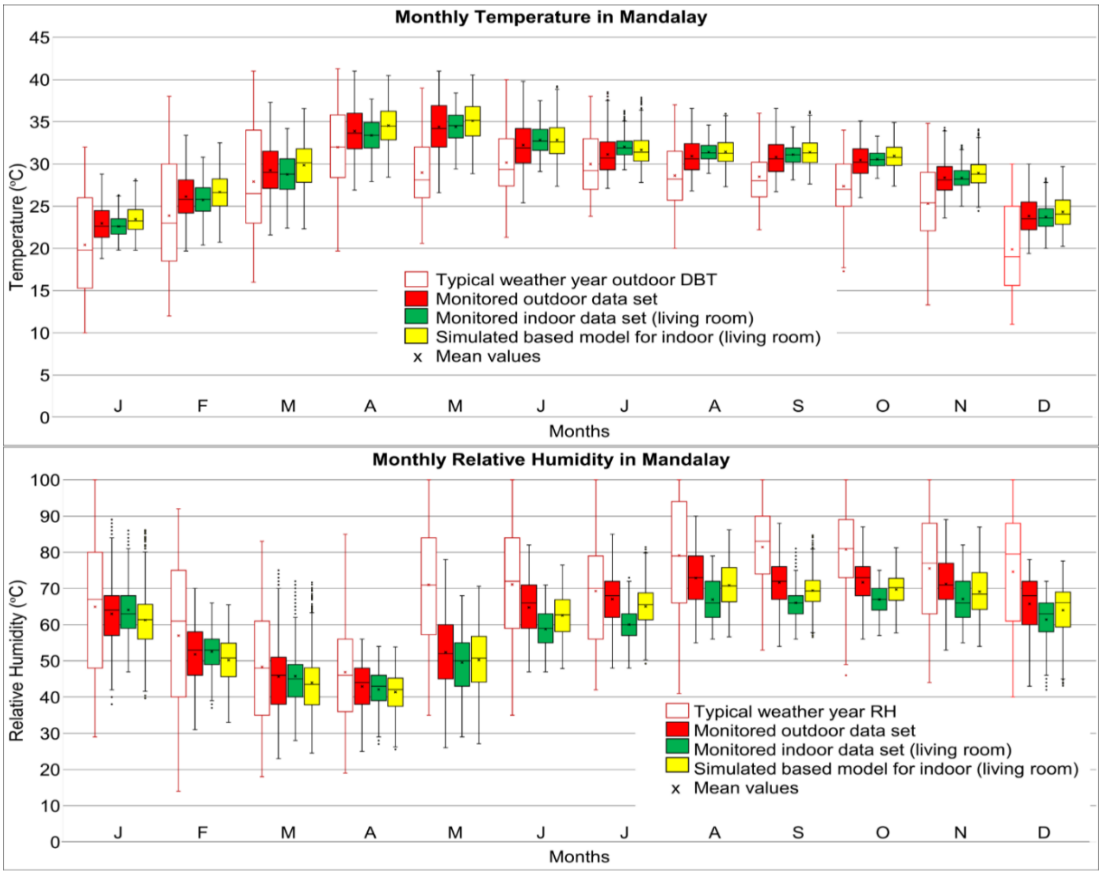


Figure 5-12. Monthly air temperature and relative humidity from a typical weather year, monitored data sets (outdoor and living room) and simulation model (living room)

During the monsoon period, the indoor humidity increased when the hot, humid air was brought inside. In the simulation model, the window W3, which is at the top of the stair space, was opened throughout the year. This was accounted for in the simulation models as high humidity was maintained both from the supply of humid air and the internal moisture gains. In the actual condition, closing the windows during a high humidity period (e.g. when it rains) also could prevent moisture from entering the dwelling. Therefore, the discrepancies could be due to the impacts of air infiltrations, internal gains, occupant behaviours for door and window opening times; while assumptions were made for these in the simulation models, exact situations in real-world scenarios could be different. Nevertheless, considerably, the simulation model had a reasonably good agreement with the monitored indoor data set, and the trends were observed to be similar.

5.2.4 Future climate scenarios

This section presents the analysis of overheating risk and vulnerability to extreme events in the future for the selected building envelopes. Similar analyses were undertaken to compare the impacts of the two-building cases on different weather scenarios. The number of days and the hourly percentage of a year in which indoor AT exceeded 30°C and 36°C are shown in Figure 5-13, from the results of the two cases for the monitored year 2019 and two future weather files.

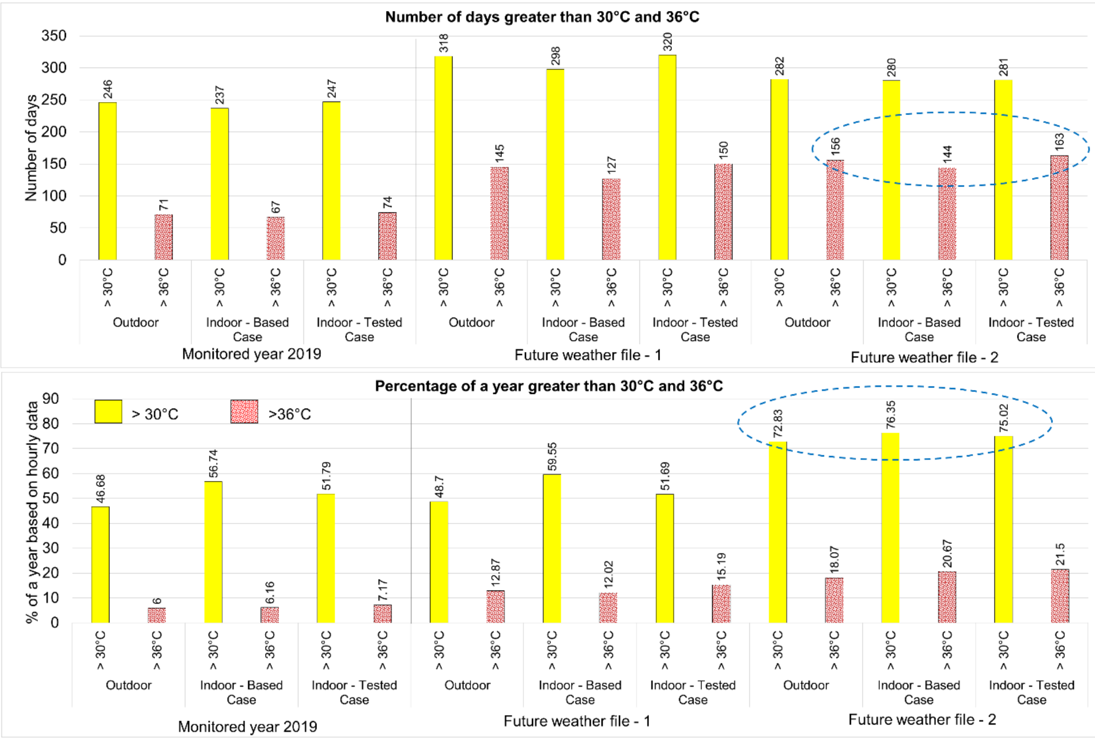


Figure 5-13. Simulated air temperatures in Mandalay dwelling (living room) – annual values

The results between the two cases indicate that the base model maintained fewer days, but more hours that exceeded the indoor AT of 30°C and 36°C, compared to the outdoor weather; the test-case model maintained more days and more hours exceed the indoor AT 30°C and 36°C, compared to the outdoor weather. The results between the two future weather files found that the future weather file-1 caused a greater number of days but a less hourly percentage of the year exceeding the indoor AT of 30°C and 36°C compared to the future weather file-2.

The monthly variations of the outdoor and indoor temperatures for the two cases for the monitored year 2019 and two future weather files were checked, and the results are shown in Figure 5-14. It was observed that there were large differences between the lower and upper extremes in the future weather file-1 due to its reference to the typical weather data. Moreover, the results of future weather file-2 showed relatively increased values against the monitored weather year 2019. The results of the base-case model showed a smaller diurnal temperature swing than the test-case model for all months throughout a year in both future weather files.

Figure 5-14. Simulated air temperatures in Mandalay dwelling (living room) – monthly values

5.3 Discussion

This section presents the findings of the monitored data sets analysis and discusses the impacts of weather changes, the performance of base-case and test-case envelopes, limitation of the study and suggested future work.

5.3.1 Typical weather data and monitored weather data

Empirical data informs evidence-based solutions based on observed and measured phenomena, is vital for a comprehensive knowledge of the local context and translating theory into real practical applications. The results of the monitored data sets had a good agreement with the "*Myanmar Climate Report"* (Aung et al., 2017) because there were changes in monsoon onset and withdrawal time in 2019. Changes in monsoon have a strong impact on the summertime high temperatures and the heat stress which occurred in the rainy season. Although there were no extreme heatwave events and considerable high temperatures in the monitored year (unlike the 2010 heatwave), the results found that the warmer hours (above 30°C) in 2019 doubled compared to its baseline typical weather year.

In this work, the HT was used in order to understand the impacts of humidity on the warm air temperature, but the heat index equation is not directly applicable to a free-running condition. The adaptive thermal comfort method enables the use of natural ventilation, while the heat balance method discourages it; moreover, people adapt to the temperatures within buildings, and they adapt the buildings themselves to suit their own thermal preferences (Roaf and Nicol, 2017). The monitored room contained one opening on each side of the wall, and the opening time of the doors and windows could be varied by the occupants throughout the year, depending on the seasons. Note that the database behind the heat index equation and the condition of the dwelling are different; therefore, further study is required for these aspects. However, according to the results for the monthly variations of HT, which were calculated from the monitored data sets, understandably, there might have a strong impact on the heat stress during the rainy season.

5.3.2 Performance of the base-case envelope

The base-case model, a model that contained material assumptions of the monitored dwelling, represented the use of thermal capacity in walls and floors but poor roof insulation. The thermal capacity of the base-case model's wall was 7.5 times higher than the test-case model. Similarly, the thermal capacity of the base-case model's ground floor was 2.5 times higher than the test-case.

The use of high thermal capacity is only effective when the nocturnal temperature noticeably drops from daytime norms; on the other hand, it is effective when the daytime temperatures reach their peak in summer.

In the monitored outdoor data set, there were small diurnal temperature swings throughout the year. However, although the peak outdoor AT reached above 41°C in April and May in the monitored outdoor data set, the peak indoor AT only reached above 37.7°C in April and 38.4°C May in the monitored indoor data set. (Figure 5-12). The psychrometric chart, which was shown in Chapter 1, Figure 1-8, notably, adding sun shading of a window was effective to improve passive cooling, and it could be more effective if all the external walls also had sun shading. With this in mind, firstly, 1.5m width horizontal sun shading was added in the base-case model, named it as 'base-case with window shading'. There were very small differences between the base-case model and base-case with window-shading only. Myanmar vernacular architecture reviewed in Chapter 1 also showed a large distance of eave projection to protect solar gain; however, the monitored dwelling had a short eave shading. Therefore, 1.5m width horizontal sun shading was added along the ground level wall, and the roof eave projection was then increased to 1.5 m. That model was named as 'base-case with wall shading'. As a result, a total of 21 hours (0.24% of the annual hour) for the indoor air temperature above 36°C were decreased in 2019 by adding sun shading. That showed the effectiveness of large eave shading for the studied climate.

In the future climate scenario, for instance, the results of the base-case model (without sun shading) for the future weather-2 (Figure 5-13) showed that there were 144 days above indoor AT 36°C while there were 156 days above outdoor DBT 36°C. However, there were 76.36% of the annual hour above indoor AT 30°C while there were 72.83% of the annual hour above outdoor DBT 30°C. The annual mean outdoor DBT for the future weather file-2 was 32.2°C. Therefore, the results of this work (both the monitored data sets and simulation results) demonstrated that if buildings have some degree of thermal capacity in their walls, this will protect against extreme outdoor temperatures, but it was also likely to maintain a high mean air temperature throughout the year.

5.3.3 Performance of the test-case envelope

The test-case model represented the use of a relatively lower thermal mass in walls and good insulation in roofs. Similar to the base-case model, 1.5m width horizontal sun shadings for all the exterior walls were added in the test-case model. In this case, the shading resulted in a decrease of 110 hours (1.26% of the annual hour) of the indoor air temperature above 36°C in 2019.

In the future climate scenario, for instance, the results of the test-case model for the future weather-2 (Figure 5-13) showed that there were 163 days above indoor AT 36°C while there were 156 days above outdoor DBT 36°C. However, there were 75.02% of the annual hour above indoor AT 30°C for the test-case model, while there were 76.35% of the annual hour above indoor AT 30°C for the base-case model. The results presented here are in agreement with the study (Nicol et al., 2005): if buildings have poor insulation characteristics or are lightweight, with low thermal capacity, they are likely to produce uncomfortable indoor temperatures during hot summers. Again, the results of this study also found a classic dilemma to choose a heavyweight or lightweight building envelope, coupled with the cooling effect of air movement in the warm-humid climate houses (Szokolay, 2000). Both heavyweight materials (base-case) and lightweight materials (test-case) have both advantages and disadvantages in the tropics in terms of their response to extreme heatwave events and typical tropical weather, and this makes it difficult to make one selection. The impacts of thermal capacity and thermal mass on the studied climate is further investigated in Chapter 6 and 7.

5.3.4 Limitations and future work

It is important to note that all simulation results contained general estimates of air infiltration and internal heat gains, and a simplification of window and door opening time and occupant behaviour in terms of thermal comfort adaptation. The discrepancies between the monitored indoor data set and the results of the simulation model were noticeable and proven to be a result of the weather data set used, which was the recommended data for this kind of work.

Therefore, a need for better data and careful consideration of its limitation was found to be crucial.

Another constraint of the thermal comfort study for the free-running buildings in Myanmar is unknown values for thermal neutrality for free-running buildings; this also relates to the way in which overheating is defined. Nevertheless, both from the monitored indoor data set and the results of the simulation model (base-case), understandably, the monitored dwelling was not able to provide thermal comfort throughout the year, and there were high overheating risks through its close response to the outdoor climate. Whilst the monitored dwelling may not be representative of all modern dwellings in Myanmar, it does represent the fundamental construction materials used and the building envelope performance for the studied climate. Despite these limitations, the findings of this study represent a substantial body of information for the monitored weather year and the importance of occupant behaviour for adaptive thermal comfort.

The integration of vernacular strategies in Myanmar housing seems to have remained remarkably resilient and is still the norm even in modern dwellings, but the use of building material has been changed. Here, the building envelope material variation in two cases manifest the common material choices in Myanmar housing. Notably, that meant there was a high U-value for the roof of the base-case model but a low U-value for the test-case model. Also, there was a high reflectivity for the roof of the base-case model but a low reflectivity for the roof of the test-case model. Furthermore, both base-case and test-case models contained different thermal properties for wall and floor materials. Therefore, the impacts of building envelope materials on the dwelling were not certain. However, a simulation study for Myanmar climates (Chapter 3) shows that adding insulation to the roofs at first is better than adding insulation (and thermal mass) in walls and floors. Furthermore, the indoor temperatures can be reduced by using high reflectivity, low solar absorptivity roofs. Although a light, cool-colour surface is suggested to reduce solar absorption and the exterior surface temperature, it also could result in a considerably high risk of condensation because mould will grow on substrates where the surface relative humidity is at or above 80%. Figure 5-7 showed that more than 4% of the annual hour in the year 2019 was above the RH 80% at the outdoor. As the RH above 80% for the indoor thermal environment was less than 1% of the annual hour, this result showed that the differences in internal surface temperatures of the building envelope would play an important role in determining whether surface condensation and mould growth will occur as a consequence of offsetting temperatures against the weather outdoor. The finding of this study further contributed that the use of thermal capacity and insulation for walls have both advantages and disadvantages for extreme scenarios and year-round thermal comfort for Myanmar climate. In this regard, further studies are needed to investigate not only how to achieve a greater thermal comfort from a combined passive strategy using ventilation, shading, and building thermal envelope performance effectively but also to avoid mould growth and condensation.

The passive design techniques used in Myanmar vernacular housing, such as pitched roofs with wide eave projections, verandas, and semi-outdoor spaces, raised floors (as presented in Chapter 3), were not included in the studied dwelling presented in this chapter. Some passive design such as raised floor seems to have disappeared in modern dwellings in Myanmar. On the contrary, an alternative design of gable vent (roof windows) use in Myanmar vernacular architecture was included in the studied house. A high-level window (W3) was opened in the studied model, which might provide air change between indoor and outdoor. However, its effect on thermal comfort was unclear in the findings. For the climate of Mandalay, the psychrometric charts showed that the use of shading and natural ventilation have more advantages for passive cooling compared to thermal mass. In this study, it was found that the effect of shading was more significant for the building with a high U-value (test-case model). Wall shading is preferable to protect the solar gain for the whole building envelope. As the usefulness of shading and natural ventilation can be varied by building orientation and other design parameters, further research is needed in that respect.

The results of the thermal performance prediction were limited by the quality of the future weather files. The weather data, whether generated either from a long-period database or from a few recent years, is a key source to predict building thermal performance design for a changing climate condition. The wind data obtained from the Netatmo anemometer was limited for wind microclimate assessment due to its location in an urban setting. Moreover, the solar radiation data used in the weather files were from satellite data. Therefore, there is a need to make climate data more accessible, which could assist research organizations and regulation and standards-setting bodies in providing their responses to climate change. Further research on shading design, natural ventilation for passive cooling, and occupant behaviour for adaptive thermal comfort are essential to quantify their impacts on the building thermal performance of free-running modern dwellings, which were left in this study. For those studies, the thermal threshold for naturally ventilated buildings in Myanmar climate is crucial, for which further research is needed.

5.4 Conclusion

Using empirical data sets and simulations, the building thermal performance study in this study combined an understanding of how the climate affected the performance of the observed building, which has a reinforced concrete structure with brick walls, concrete floors and a metal roof. Regarding the building thermal performance prediction for future climate scenarios, the simulation experiments were carried out for validation and building thermal performance prediction for two different building envelopes. At the outdoor weather condition, in terms of DBT alone, the results found that the warmer hours above 30°C in 2019 doubled compared to its baseline typical weather year. The effect of monthly RH changes between a typical weather year and the monitored year 2019 was found in the monthly results of WBT and HT due to the increased DBT. In terms of heat stress, 14.06% of the annual hour were found as a 'danger' heat index temperature stage in 2019, while there were only 5.49% of the annual hour in the typical weather year data. At the indoor condition, the indoor thermal environment the monitored dwelling performed closely to the weather outdoor, but there were considerable offsets for the daily peak temperatures and humidity. In essence, the findings indicated that free-running (modern) dwellings in Myanmar face two fundamental challenges for thermal comfort: high vulnerability to extreme heatwave events and underperformance for increased heat index temperature.

Using a single database with limited assumptions in simulations, it is impossible to determine which design inputs are relatively more effective to improve the thermal performance of Myanmar dwellings in response to extreme summer overheating and to achieve year-round thermal comfort in future climate scenarios. Although these in situ monitored datasets and simulations were limited, the findings of this study contribute valuable insights as follows.

- An understanding of the vulnerability of homes to overheating in Myanmar, particularly from the impact of climatic elements on thermal comfort: the findings showed evidence of the health risks in Myanmar in terms of heat stress which is accessed using wet-bulb and heat index temperatures.
- An understanding of the impacts of changes in monsoon onset and withdrawal time, warmer night temperatures, and the urban heat island effect on the indoor thermal environment: the results of the analysis showed how the combined effect of air temperature and humidity could be changed in the future climate scenarios compared to the typical weather year and the historical weather year 2019.
- An understanding of the material property selection for the Myanmar climate: the study compared the impacts of building envelope with vernacular materials (test case) and further modified with modern materials (base case as the observed condition), in terms of their different capability to offset the extreme temperatures and adjust daily mean temperatures, and also discussed the effect of humidity in the study climates.

Myanmar is still a country with a poor health care system, inadequate legislation, and limited research about thermal performance building design. Nevertheless, the country is exposed to the global risks of climate change, and as a tropical country, it is particularly vulnerable to some of these. On the national scale, Myanmar needs systematic and comprehensive research for building thermal performance design, both for short-term and long-term changing climate conditions. Further studies are necessary analysing large monitoring data sets with more rigour for validation of building thermal performance for various built forms and different building types that will create a more robust evidence base for use in sustainable designs adapted to future climate scenarios.

Overall, this chapter provides a record of one-year empirical data set for two cities to enhance the reliability of findings from the simulation case studies (Zune et al., 2020b, 2020e) and contributes to valuable insights such as an understanding of the vulnerability of homes to overheating in Myanmar, particularly from the impact of climatic elements on thermal comfort, the impacts of changes in monsoon onset and withdrawal time, warmer night temperatures, and the urban heat island effect on the indoor thermal environment, and the impacts of different building envelope material properties (Zune et al., 2020b, 2020e).

Acknowledgements: The author gratefully acknowledges the homeowners of the monitored dwelling for their agreement and help of the field measurements and the University of Nottingham for the Netatmo equipment.

This is the year 2019.

This is not the time and place for dreams.

This is the time to wake up.

This is a moment in history

where we need to be wide awake.

~ Greta Thunberg

at US Congress, Washington DC, September 2019

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6. Assessing the Effectiveness of Shading and Roof Materials using Passivhaus Parameters

Due to the success of Passivhaus principles in reducing building operational energy use and regulating indoor comfort in European climates, the potential implementation of it in other climates has been subjected to much attention in the last few years. The combined results of shading design and Passivhaus thermal building envelope properties remains a novel area of theoretical and practical research to adapt Passivhaus in the tropical climate contexts. The literature review discussed in Chapter 2 highlighted that 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). Shading offers a microclimate modifier by reducing the outdoor thermal stress and direct solar heat gain. Shading design often concerns aesthetics (Fiorito et al., 2016), building energy conservation (Aflaki et al., 2015), and climate change adaptation (Hooff et al., 2014) for building thermal comfort, particularly for tropical buildings in extreme environments (CIBSE, 2017). Even highly insulated and airtight Passivhaus buildings with active ventilation can face a summer overheating risk (Mitchell and Natarajan, 2019). Therefore, optimisation of several design inputs for Passivhaus buildings, including external shading devices, thermal mass effect, and glazing ratios are becoming increasingly relevant to prevent summer overheating even for the temperate climates of the United Kingdom (Abdulla and Rodrigues, 2016, McLeod et al., 2013, Osterreicher and Sattler, 2018, Rodrigues et al., 2016, Rodrigues and Gillott, 2013).

Although increasing thermal mass and adding more insulation is an approachable design for tropical Passivhaus design, Myanmar housing needs to address the requirements of thermal performance design for climate change adaptation and earthquake-resistant design for the Sagaing fault (Figure 1-5). For the Passivhaus concept to be effective in tropical countries and future climate change scenarios, there is a need for a detailed investigation of the contribution of passive strategies such as shading to the overall balance and of the possibilities of relaxing the building envelope parameters to suit local contexts. This was a gap in the current literature, and therefore, the focus of the first section was to investigate the synergistic effects between shading and Passivhaus building envelope design for a tropical climate context to improve the building thermal performance. The second section was to investigate the impact of roof insulation and cool roof effect in the Myanmar climates, from which it can be understood whether the insulation and building weight can be reduced by considering solar absorptivity and reflectance values.

6.1 Shading study

Building design for the cold and tropical climates differs significantly due to their climatic parameters that directly affect the selection of thermal transmittance (U-values) properties for insulation and ventilation strategies. The U-values for the opaque envelope in a Central European Passivhaus range from 0.10 to 0.15 W/(m²K); these 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, p24-25). Evidence (Table 6-1) showed that Passivhaus buildings in tropical climates are mostly built with slightly higher U-values than the Passivhaus criteria for cold climates and have additional design features to meet the local contexts differently (Bere, 2013, Oettl, 2012, Passive House Database, 2020, Yeh, 2020).

Therefore, it was 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, a methodology was developed that underlined the synergistic effects between shading and Passivhaus thermal building envelope, particularly the effectiveness of thermal mass and insulation to meet the building cooling for the extreme temperature conditions of the tropical climates. It was attempted to understand whether this hypothesis is true for the Myanmar climate and which other parameters influenced the comfort levels. Note that the hypothesis presented in this chapter was aimed to support the main hypothesis discussed in the 'Introduction' section.

Table 6-1. 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 (Passive House Database, 2020)	4340	5892	6340
U-values of walls, W/(m²K)	0.320	0.210	0.16
Roof, W/(m²K)	0.290	0.135	0.20
Floor, W/(m²K)	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 in the floor.	An irrigation system that can save up to 70% water.	Light colour finishes and shade on the walls.
Reference	(Bere, 2013, Oettl, 2012)	(Passive House Database, 2020)	(Yeh, 2020)

6.1.1 Study Models

Investigating the synergistic effects between external shading, Passivhaus envelope materials, 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 optimization methods. Each building plan and built form have both advantages and disadvantages; therefore, it must determine which configurations have the most pronounced impact on building performance. Using a real-world 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).

In this study, following the first simulation exercises presented in Chapter 3, 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 had 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 (Figure 6-1) were defined according to the roof forms: model group A had a flat roof with no roof extension, model group B had a flat roof with 0.5m roof extension, model group C had a flat roof with 1m roof extension, model group D had a gable roof with 0.5m roof extension, and model group E had a gable roof with 1m roof extension. 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 TFA. The door had a 1.2m width and 2.2m height. The window had 2.2m in width and 1.8m in height. In order to keep a consistent format, the window of the model group D and E were set at the same size.

Mandalay was selected for this study. In Mandalay, high solar radiation can be found during the solar time, from 9:00 a.m. to 4:00 pm. As the solar altitude angles vary from 30˚ to 85˚ at the summer solstice solar time, a wide overhang can partially protect the direct sun. Therefore, a window overhang shading was initially considered in this study. On the other hand, in Chapter 4, it was found that adding sun shading to a window is effective to improve passive cooling in Mandalay, and it could be more effective if all the external walls also had sun shading. Therefore, 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 6-1) for this study.

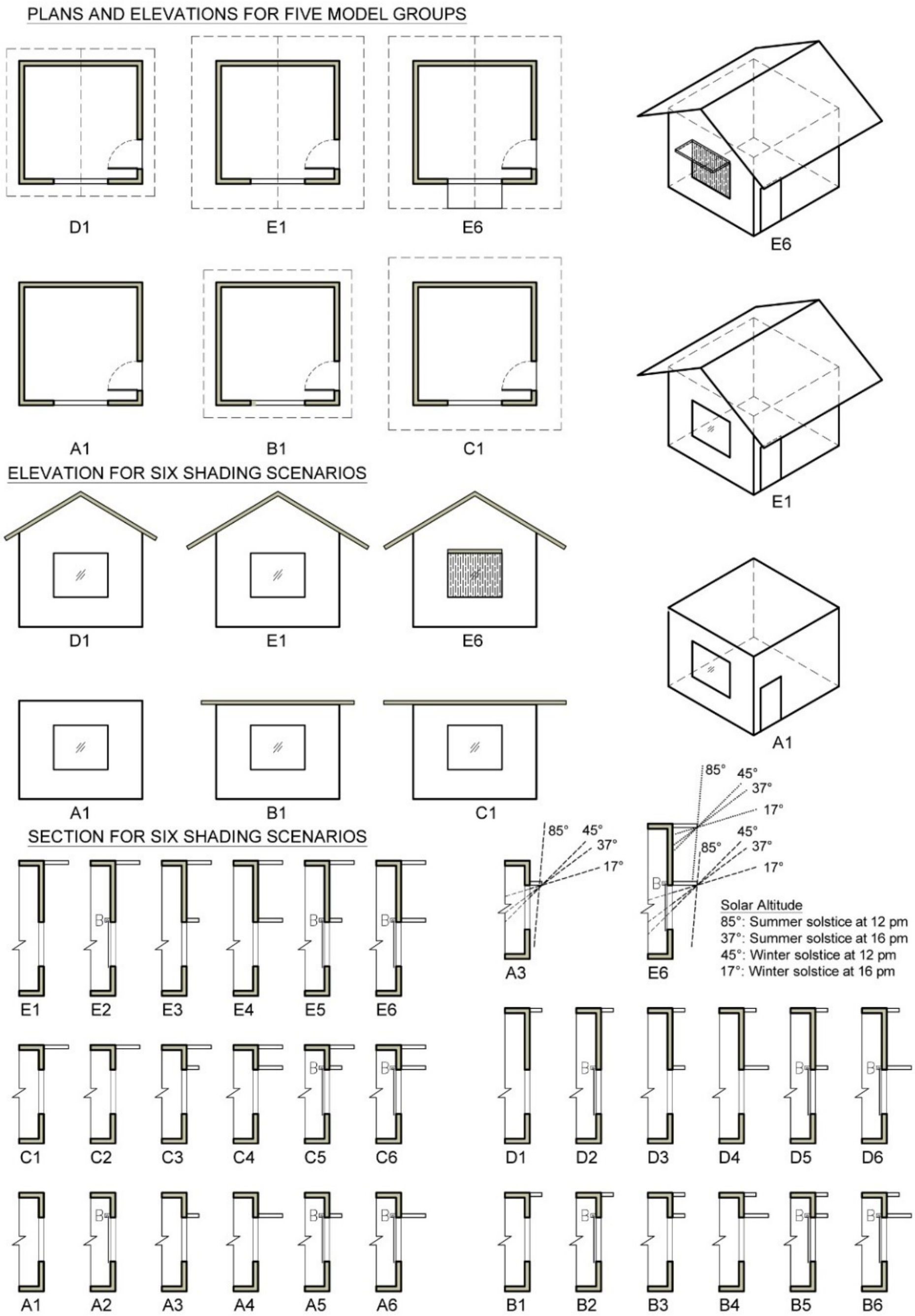
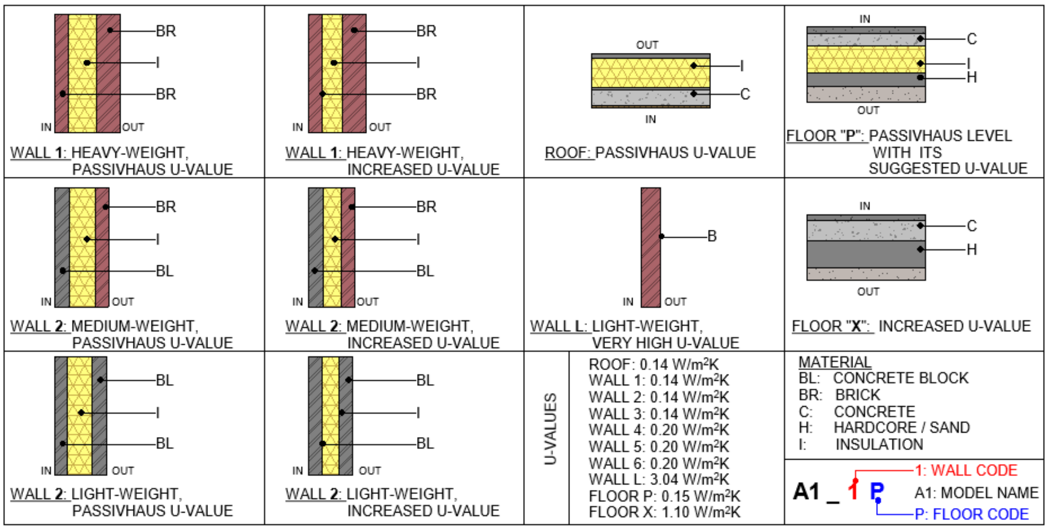


Figure 6-1. Example plans, elevations, and isometric model of the simulation models with different shading types on the south elevation

A dynamic simulation program was used to model a range of individual interventions to understand the general evolution of Passivhaus building envelope material properties and shading design, with recent climate data and predicted future climate scenarios of Myanmar. 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). Unlike the PHPP calculation, the impacts of revealing shadings on the building thermal performance were not fully captured in the IESVE models.

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 6-2 and Table 6-2.

(a) Building materail code used in this study



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

A1_1P	: Model A1 with Heavy-weight Passivhaus wall and Passivhaus floor	a) Passivhaus building envelope configurations
A1_2P	: Model A1 with Medium-weight Passivhaus wall and Passivhaus floor	
A1_3P	: Model A1 with Light-weight Passivhaus wall and Passivhaus floor	
A1_1X	: Model A1 with Heavy-weight Passivhaus wall and increased U-value for floor	b) Partial Passivhaus building envelope configurations
A1_2X	: Model A1 with Medium-weight Passivhaus wall and increased U-value for floor	
A1_3X	: Model A1 with Light-weight Passivhaus wall and increased U-value for floor	
A1_4X	: Model A1 with Heavy-weight increased U-value for wall and increased U-value for floor	c) Non-Passivhaus building envelope configurations
A1_5X	: Model A1 with Medium-weight increased U-value for wall and increased U-value for floor	
A1_6X	: Model A1 with Light-weight increased U-value for wall and increased U-value for floor	
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 6-2. Simulation codes based on model name and building material codes

Table 6-2. Building envelope configuration used in this study

Building envelope configuration	U-value (W/m²K)	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	102	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				

*Regarding the window's g-value, which is the solar heat gain coefficient of the glass, the PHPP suggests glass with a g-value of 0.5 means that 50% of the solar heat is transmitted through the glass (Feist et al., 2019). However, the studied climate here was warm and humid; therefore, a lower g-value of 0.37 was considered in this study.

Three materials sets were proposed to investigate in the simulation study, namely: (a) Passivhaus building envelope configurations (full compliance with Passivhaus U-values), (b) Partial Passivhaus building envelope configurations (compliance with Passivhaus U-values for wall and roof, but increased U-value for the floor); and (c) Non-Passivhaus building envelope configurations (not complying with Passivhaus U-values in walls and floor, but with Passivhaus U-value in the roof). Furthermore, each building envelope configuration was subdivided into three different thermal mass types (heavy-weight, medium-weight, and lightweight). Also, a very lightweight but high 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 6-2) were roughly selected to differentiate the U-values between the Passivhaus level and the increased U-value of the Passivhaus level.

6.1.2 Methodology

The building energy and thermal performances of a Passivhaus building are estimated using a steady-stage, heat balance thermal/energy model, which is generated from the laws of physics using the Passive House Planning Package (PHPP). The Passivhaus uses MVHR for the heating seasons but often rely 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 (no active cooling or heating) adaptive comfort model. Therefore, 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, as a first step, the two sections were presented in the literature review (Chapter 2): “the thermal comfort quantification” for free-running Passivhaus buildings in tropical climates and “simulating comfort in buildings”. That reviewed allowed this study to identify different thermal comfort benchmarks for the comparison of the results generated from different simulation studies.

The second step was to undertake 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). 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 the impacts of other parameters that are not included in the PHPP calculation were investigated.

Thirdly, using IESVE, a dynamic model in the CIBSE system of model classification, the synergistic effects between shading and Passivhaus thermal building envelope in a tropical climate were investigated. Unlike the PHPP, the results generated from the IESVE were calculated for the 24 hours of each design day, on the hour (IESVE, 2015). Many scholars also have used the IESVE for the Passivhaus research with a focus on thermal analysis and shading design (Abu-Hijleh and Jaheen, 2019, Aldossary et al., 2017, Costanzo et al., 2020, McLeod et al., 2013). In the dynamic simulation study, the hypotheses were tested using different weather scenarios, including predicted future climate scenarios of Myanmar that identify unresolved issues of the Passivhaus envelope in a tropical climate.

6.1.3 Calculation and simulation cases

Internal heat gain, ventilation profiles, and weather scenarios were firstly defined to calculate the indoor air temperature properties of the 30 models (Figure 6-1) with ten different building envelope material properties (Figure 6-2 and Table 6-2).

In this study, the internal (sensible) heat gain was set as 2.1 W/m^2 in the IESVE simulation program with a continuous profile, which is the default PHPP internal heat gain for a single-family home (Feist et al., 2019); the latent gain was not considered. The Passivhaus standard asks the air change rate at the pressure test n_{50} to be less than 0.6 ACH (Feist et al., 2019). The Passivhaus suggests a typical infiltration rate as 0.042 ACH based on 0.6 ACH @ 50Pa for air infiltration; that value was used in this study, although this study was particularly focused on a free-running mode with natural ventilation. 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 a.m. to 06:00 p.m. Night-purge ventilation plays a critical role to cool and discharge accumulated heat from the mass. Therefore, three window opening profiles – 24 hours open (including night-purge ventilation), 24 hours close, and daytime open – 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 four weather files (i.e., typical, recent, and two future climate scenarios. A typical weather file was produced by Huang et al. (2014), which accounts for the years between 2005 and 2013. A historical weather file for the year 2019 and two future weather files produced in Chapter 5 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 a 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. Both future weather files were created by adding increased value 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) and (Cox et al., 2015). 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.

6.1.4 Steady-state Passivhaus calculation

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 summertime), and temporary sun protection (e.g., the percentage of activation factor).

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, which is built with solid constructions and is oriented exactly towards the south. Darmstadt, a city in southwest Germany, is located at 49˚N and has a mild warm temperate climate. It has 156m^2 of the treated floor area (TFA), 665m^3 of the enclosed volume, 184.3m^2 of the exterior walls, and 43.5m^2 of window 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., its 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 can 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 6-3; the temperature data of 19 cities was taken from the PHPP software; the temperature data of Myanmar is from ASHRAE (Huang et al., 2014) and Chapter 5. There were significantly higher monthly temperatures in Mandalay (Myanmar), Manila (Philippines), and Miami (USA) than in other cities. Note that the monthly average outdoor temperature of Darmstadt (Germany) is lower than 25°C, whereas the tropical climate of Mandalay (Myanmar) has 67.8% of annual hours above the outdoor dry-bulb temperature of 25°C.

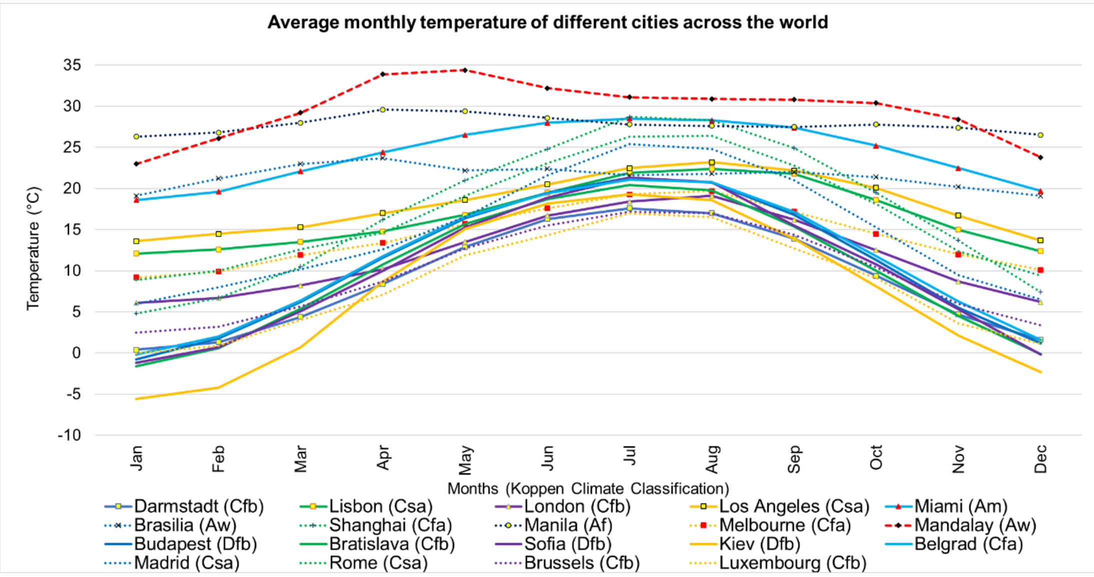


Figure 6-3. The average monthly temperature profile of 19 cities with their Koppen climate

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 is switched from Darmstadt to other cities, the building was not meet the Passivhaus requirements of comfort and energy criteria. Therefore, the results of Figure 6-4a 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, Shanghai, Manila, 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, Manila, and Mandalay due to the impacts of tropical and hot climate contexts (Figure 6-4b).

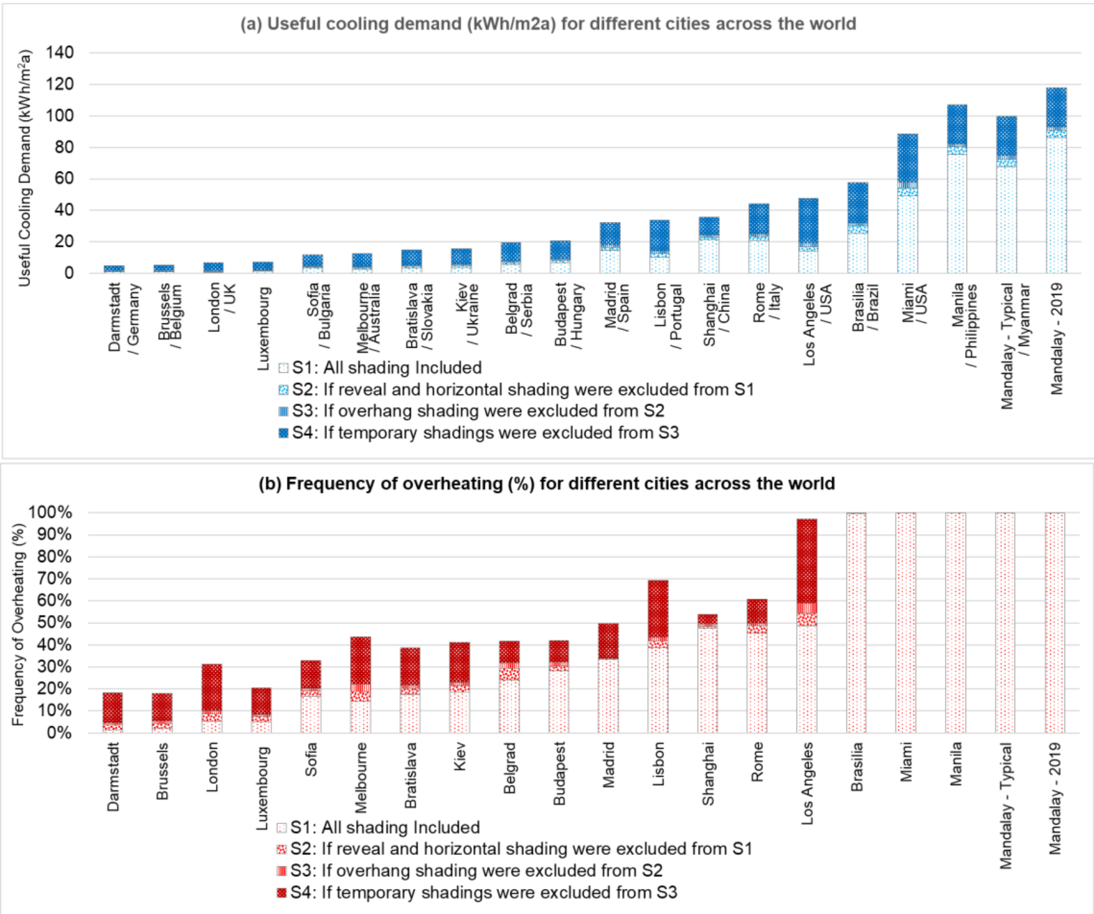


Figure 6-4. Shading design through the use of steady-state PHPP calculation for the test building

The Passivhaus suggests that the space heating and cooling demand not exceed 15 kWh/m^2/year which is Performance targets for a European climate;

therefore, it was found more than 80 kWh/m^2/year of space cooling load in Figure 6-4 for Miami, Manila, 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 is an unsurprising result for 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 6-4) revealed that there were significant impacts of outside climates and temporary shading on the tested building. The PHPP calculation provides in-depth details of shading calculation through different shading reduction factors; that shows a small amount but noticeable results in Figure 6-4 (see S2: if reveal and horizontal shading were excluded from S1). On the other hand, Figure 6-4 revealed that the Passivhaus standard is applicable in the Myanmar climate following its steady-state calculation with mechanical ventilation; however, it is necessary to solve significant cooling load requirement and overheating problems.

6.1.5 Dynamic simulation results

The results were presented to check – 1) which studied model scenario performed better than others; 2) when was the most overheated time and how many annual hours were above 30°C and 36°C; 3) how do temperatures vary in the studied models?

6.1.5.1 Results for daytime window opening scenario

Firstly, the temperature range of 30 models was presented for a "daytime window opening scenario" to investigate how the indoor air temperatures were changed when building envelope configurations were switched from 1P to LX. Figure 6-5 showed that 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 this scenario. 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, but there was a drawback of a high mean temperature throughout a year compared to the building envelope with lightweight, high U-values walls.

Secondly, 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 the changes in building envelope materials (10 building envelope configurations), rather than differences in building typologies and shadings. However, the impacts of building typologies and shadings were found when the model A6 was compared to models C6 and E6. The percentage of annual hours above 30°C was significantly reduced in the models E6 compared to the models A1 (Figure 6-6). 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 found an impact on building height. The building envelope configuration LX showed the best scenario if the indoor temperature was checked with 30°C benchmarks.

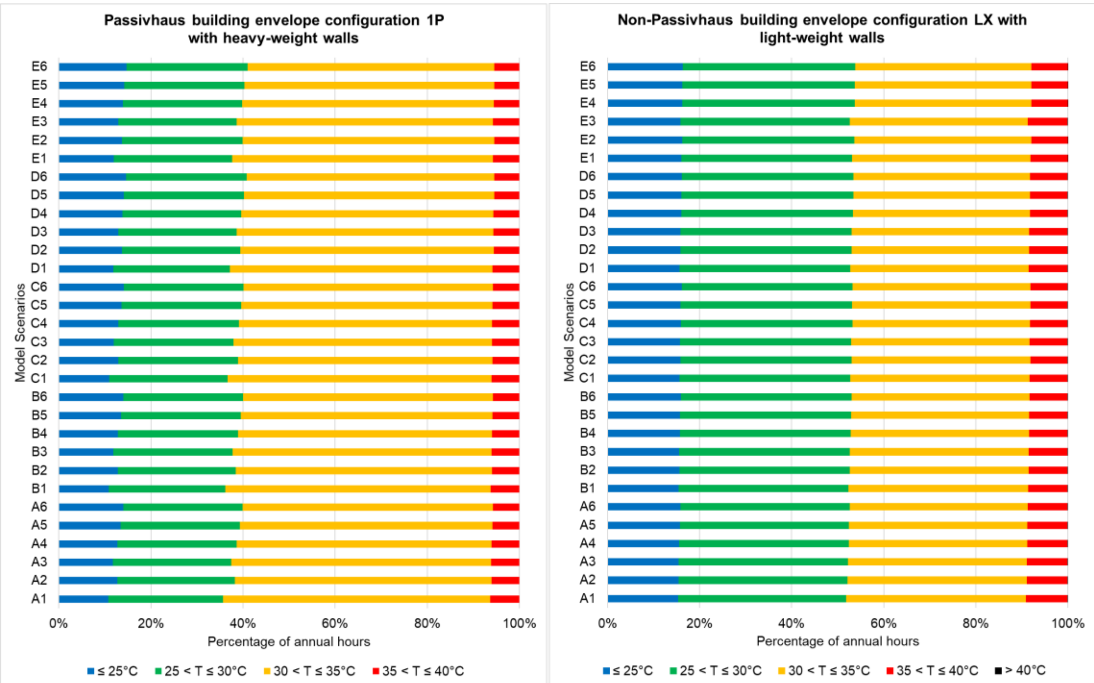


Figure 6-5. Temperature range found in 30 model scenarios, presented for building envelope configuration 1P and LX for a typical weather year (P: Passivhaus level with its suggested U-value; X: Variation in Passivhaus levels with increased U-value), daytime window opening scenario

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. Therefore, 36°C was used as a benchmark to check the thermal discomfort time of a year and the impact of the four different outdoor climates. The results are shown in both Figure 6-6 and Figure 6-7 that indicates the model A1 gained the highest percentage of the annual hours above 36°C, while the 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 difference between C1 and E1 was the building height; the model E1 performed slightly better than the model C1 - that showed the importance of ventilation volume even for the same TFA. Unlike the results of Figure 6-6, 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. The models with building envelope configurations 1P, 2P, and 3P received higher percentages of the annual hours above AT 36°C than the other scenarios (1X, 2X, 3X, 4X, 5X, 6X).

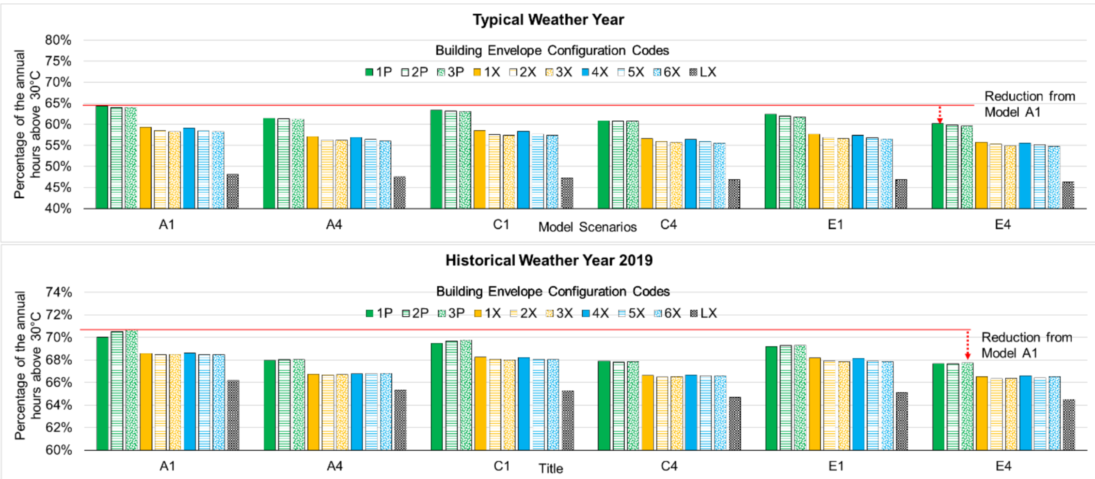


Figure 6-6. Percentage of a year above indoor air temperature 30°C in model group A for 10 building envelope configurations, presented for a typical weather year and historical weather year 2019, daytime window opening scenario

For the two future climate scenarios (Figure 6-8), indoor air temperature 40°C was used as a benchmark to check the impacts of extreme thermal discomfort. The results (Figure 6-6, Figure 6-7, and Figure 6-8) 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 files showed that reducing the insulation on the floors was more sensitive in the future climate weather - 2 as the night-time temperatures increased. In Figure 6-7, for the model A1 with building envelope configuration 1P scenario, with 36°C benchmarks, 3.82% of annual hours were found in a typical weather scenario, but it would be 30.88% in a future weather scenario-2, which was eight times increment. Figure 6-5 was not able to present the temperature range above 40°C. Figure 6-8 shows that the models with building envelope configurations LX received the highest percentage of annual hours above 40°C, which was significantly higher than the outdoor condition, due to its poor U-value of the wall while windows were opened only daytime.

Annual regression plots of the models A1, C6, and E6 for the building configurations 1P, 3P, 1X, 4X, and LX were presented in Figure 6-9 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 the model E6 with building configurations 1X and 4X, proving the hypothesis is true. The worst scenario was found in the results of model A1 with building configuration LX. The daily minimum and maximum temperatures of the models A1, C6, and E6 for building envelope configurations 1P and LX were presented in Figure 6-10. In the future weather scenario-2, it was found that the models with building envelope configurations 1P maintained lower maximum temperatures but higher minimum temperatures than the models with building envelope configurations LX. The results of Figure 6-9 and Figure 6-10 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.

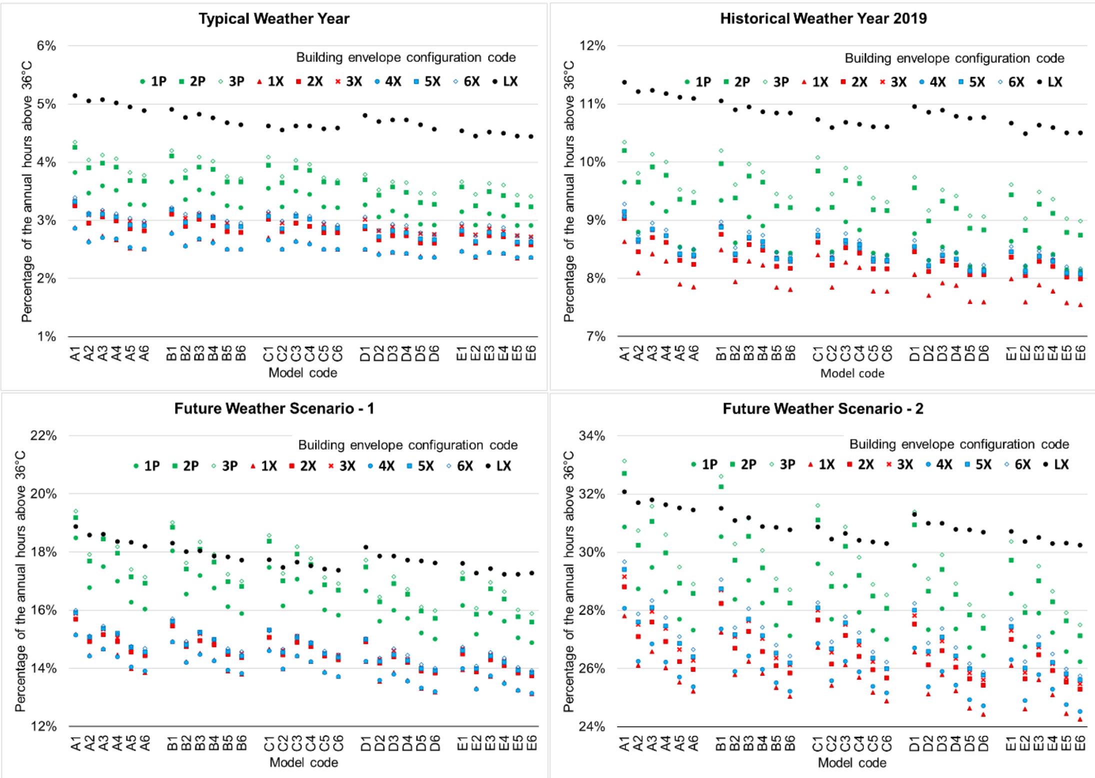


Figure 6-7. Percentage of a year above indoor air temperature 36°C in 30 models with 10 building envelope configurations, presented for a typical weather year, historical weather year 2019, and two future climate scenarios of Mandalay, daytime window opening scenario

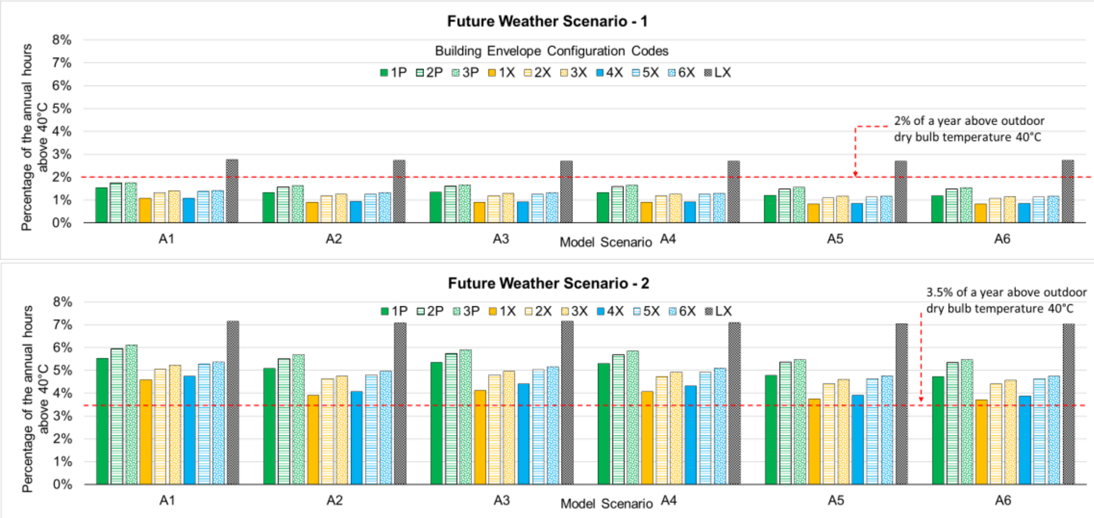


Figure 6-8. Percentage of a year above indoor air temperature 40°C in model group A with 10 building envelope configurations, presented for two future climate scenarios of Mandalay, daytime window opening scenario

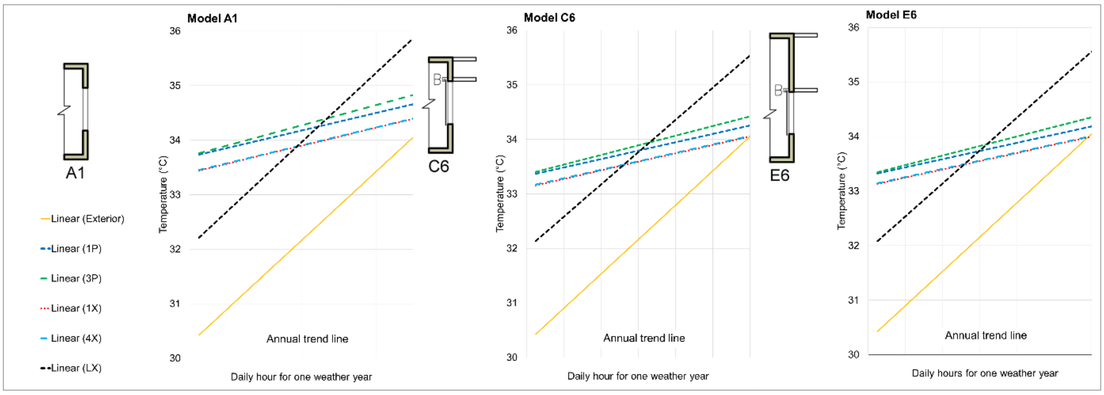


Figure 6-9. Annual regression plots for models A1, C6 and E6 for future climate scenario-2, presented for different building envelope configuration scenarios

Figure 6-11 illustrates the 24-hour profile of indoor air temperature for the hottest day of the year, showing different results of nine building envelope configurations using model A1 for a daytime window open scenario. It was found that the models with heavy-weight walls (code: 1P, 1X, and 4X) maintained low temperatures, and the models with lightweight walls (code: 3P, 3X, and 6X) gained high temperatures; the differences were less than 1°C. Figure 6-11 also illustrates the 24-hour profile of indoor air temperature for the peak day, showing different results of shadings using building envelope configuration 1P as a sample. It was found that the model A6, which had a 1m roof extension and a 1m window overhang with internal shading, had a lower temperature than the other models; however, again, the differences were less than 1°C.

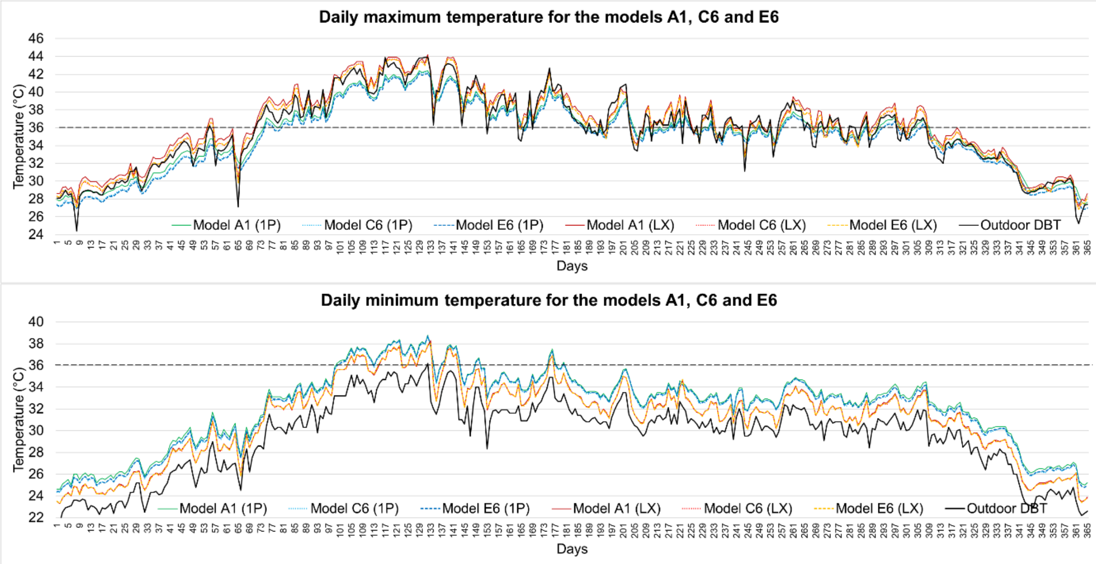


Figure 6-10. Daily minimum and maximum temperatures of models A1, C6 and E6 for future climate scenario-2, presented for different building envelope configuration scenarios

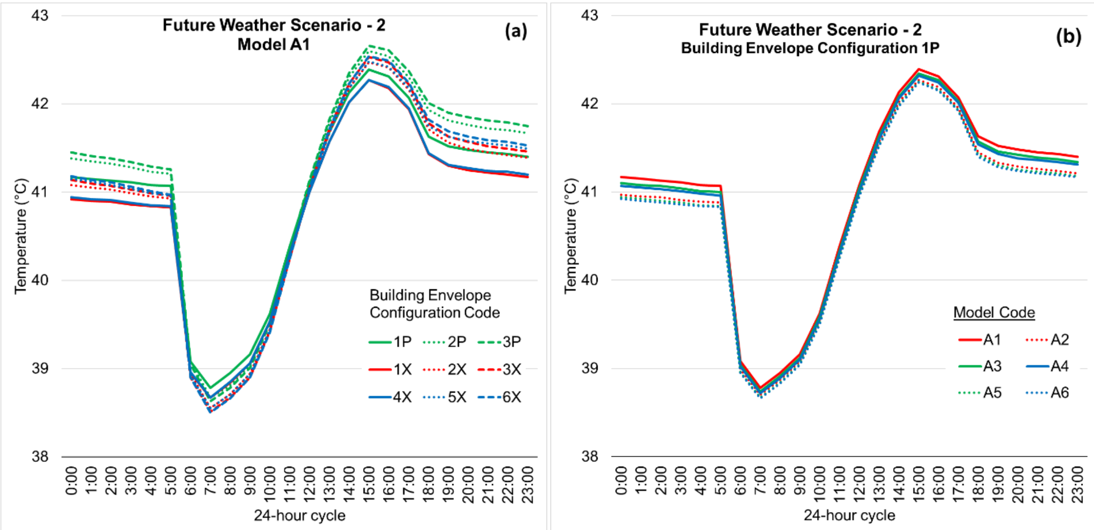


Figure 6-11. 24-hour profile of indoor air temperature showing different results of (a) Nine building envelope configurations using model A1, and (b) Six models using building envelope 1P, presented for the hottest day of future climate scenario-2 of Mandalay

6.1.5.2 Results for three scenarios of window opening profiles

As the window opening has a significant impact on indoor thermal comfort, the effect of "three window opening scenarios" was checked by repeating the same simulation scenarios. Regarding building envelope configuration, significant performance differences were found between 1P and 6X (Figure 6-11). Therefore, it can be expected to see differences between 1P and LX if they were compared- 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 high U-value. The annual regression plots of the models

A1, C6 and E6 for future climate scenario-2 (Figure 6-12) 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 the model E6 with night-purge ventilation as the mean temperature of about 2°C can be reduced by switching the building envelop from LX to1P. 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 solid green lines); that showed the effectiveness of shading with high thermal mass.

When the windows of the models A1, C6, and E6 were open daytime only in the results of Figure 6-10, 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 will be required in the daytime throughout the hot and wet seasons if windows were open daytime only. On the contrary, for the model E6 in the future climate scenario-2, if night purge ventilation was considered, mechanical ventilation will be required at day time only throughout the hot and wet seasons (Figure 6-13). Overall, the regression plots with daily hours and daily maximum/minimum temperature profiles showed the positive results of nigh-purge ventilation with high thermal mass, although it also caused the expense of elevated mean temperatures.

Figure 6-14 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, with a larger diurnal temperature swing than the models with building envelope configuration 1P.

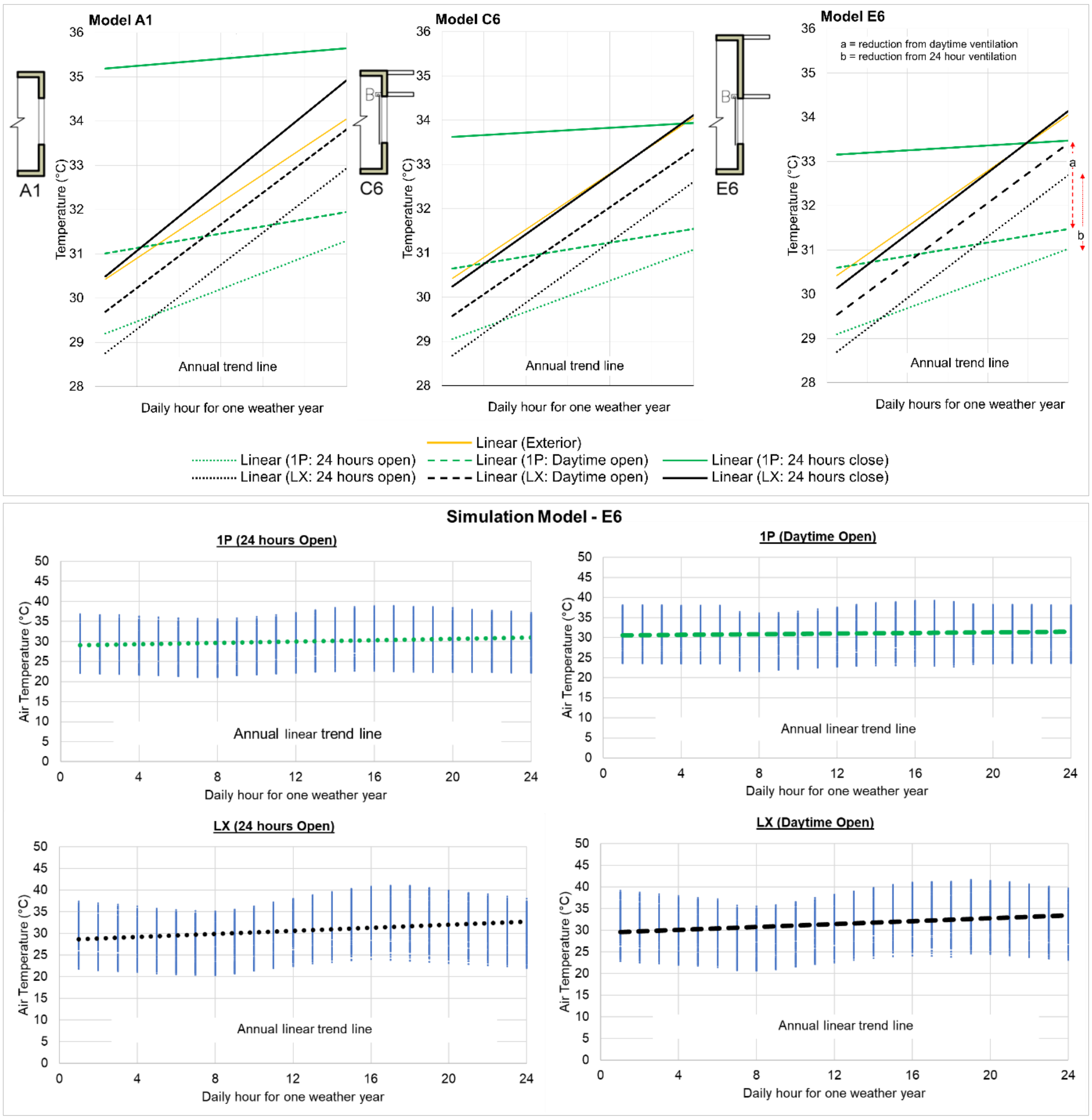


Figure 6-12. Annual regression plots for models A1, C6, and E6 for future climate scenario-2, presented for different window opening scenarios

The models with 24-hour closed window scenario were the worst scenario, with the smallest diurnal temperature swing. 93.6%, 82.4%, 72.8%, 42.51% and 18.1% of annual hours were found to be with the air temperature above 25°C, 28°C, 30°C, 33°C, and 36°C, respectively. The results of decrement delay and differences between peak external and internal temperatures were found for the models with building envelope configuration 1P (Figure 6-14). Although the differences between the models A1 and E6 were not obvious in the 24-hour profiles of Figure 6-14, the results of the model E6 (Figure 6-12 and Figure 6-13) showed that the effectiveness of shading was more obvious if the models had a high thermal mass in walls (e.g., 1P).

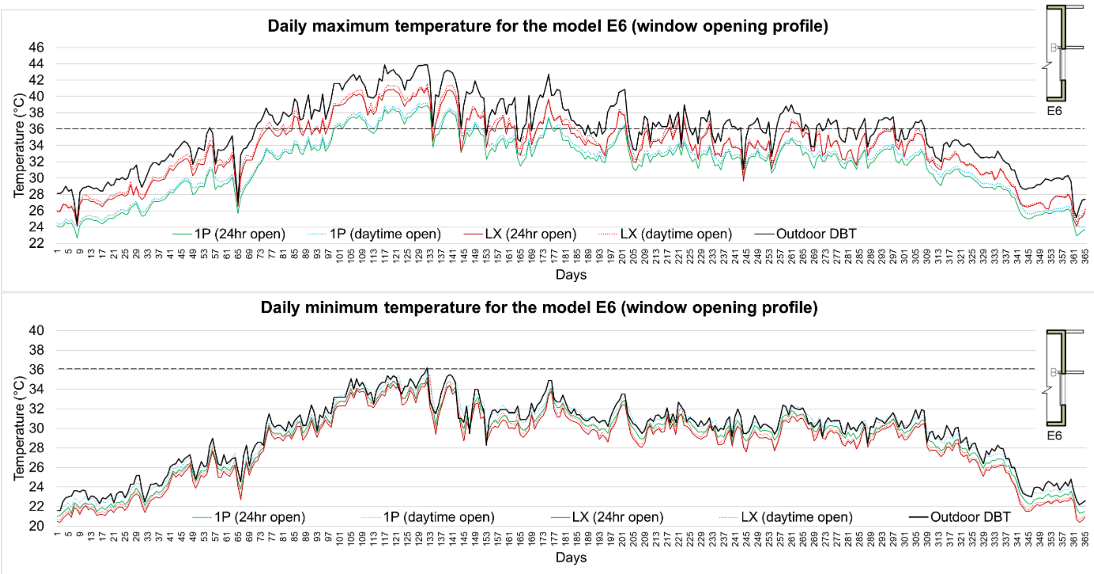


Figure 6-13. Daily minimum and maximum temperatures of the model E6 for future climate scenario-2, presented for two window opening profiles

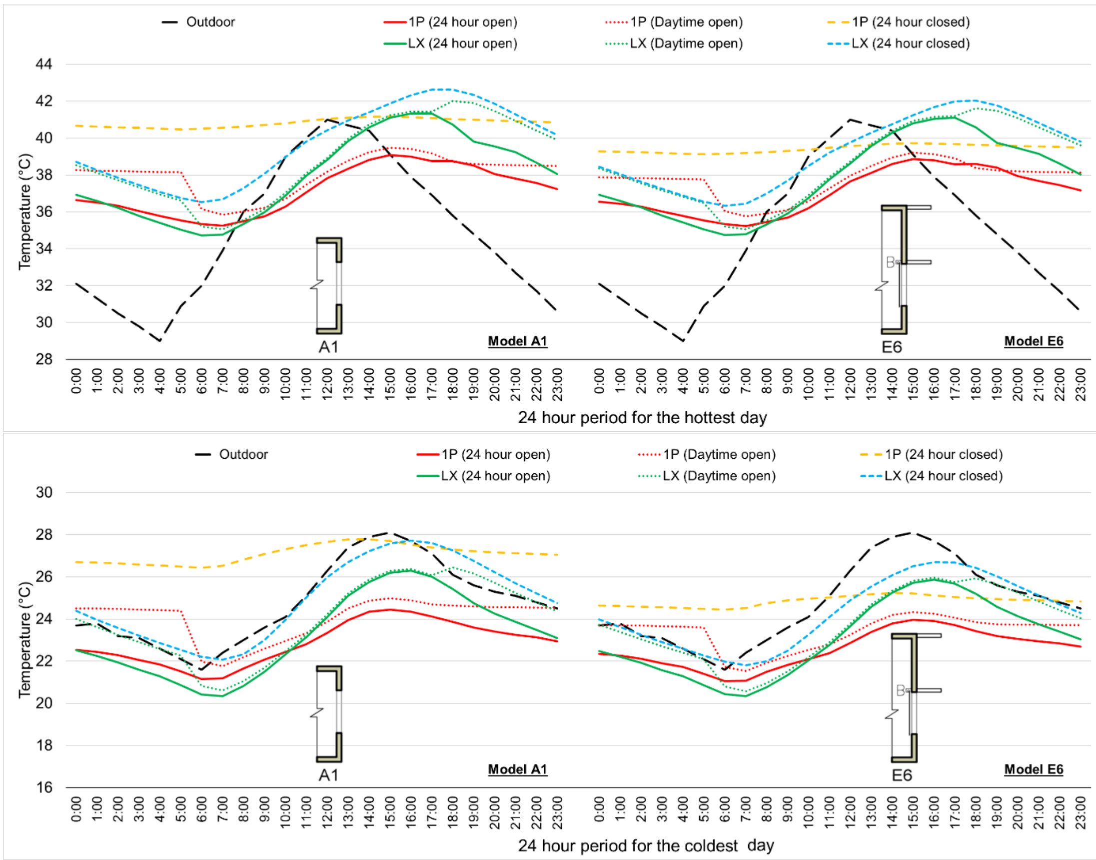


Figure 6-14. 24-hour profile of indoor air temperatures for the hottest and coldest days showing two building envelope configurations (1P and LX) for models A1 and E6, compared with the outdoor dry bulb temperature of the year 2019

6.1.6 Discussion

In this section, based on the results of 30 models from their temperature profiles (annual mean temperatures, daily maximum and minimum temperatures, temperature range, and hottest and coldest day temperatures) for different building envelope configurations, a discussion is presented considering the impacts of U-values, thermal mass, shading and ventilation on the simulated models.

Impacts of U-values: The simulation results presented in this study revealed that the wall and floor types with slightly higher U-values than Passivhaus criteria (0.20W/m^{2}K for walls and 1.11W/m^{2}K for floors in this study) 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 6-6, Figure 6-7, Figure 6-8, and Figure 6-9. Likewise, the wall's U-values with slightly higher U-values than the Passivhaus' suggestion performed better in the studied climate (see the building envelope configuration 1X, 2X, 3X, 4X, 5X, and 6X), even in the future climate scenarios.

Impacts of thermal mass: The results of the models with building envelope configuration 1P showed the effectiveness of thermal mass and night-purge ventilation in the studied climate. The effect of thermal mass was less obvious with high-temperature benchmarks of 36°C and 40°C (Figure 6-7 and Figure 6-8) than with the results for the benchmark 30°C (Figure 6-6). In Figure 6-8 for future climate 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 6-14). Therefore, a careful examination needs to be worked in selecting the building material for its thermal capacity and U-values.

Impacts of shading: Switching the model A1 to A6 by adding different shadings showed the sensitivity of shading in thermal performance. For the future climate scenario 2, Figure 6-7 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 could be reduced by using shading with the high thermal mass Passivhaus building envelope. It was also found that slightly different indoor air temperatures for the 24-hour profile were observed (Figure 6-11) for six shading scenarios. 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: It was found that the positive results of nigh-purge ventilation with high thermal mass, although it also caused 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; that showed there was a need for mechanical ventilation to maintain thermal comfort consistently throughout the year. In the practices, all Passivhaus projects have been designed with one 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. For a naturally ventilated building, there is a benefit of controlling the windows opening, but it is occupancy-dependent in improving their thermal condition; future studies are required for all those considerations.

Mechanical ventilation requirements: The differences between Passivhaus and non-Passivhaus building envelope configurations were found both in annual temperature ranges and peak air temperatures. However, by switching lightweight building envelope (LX) to heavy-weight Passivhaus construction

(1P), it was found that the maximum mean temperature of about 2°C can be reduced, and the positive results were more obvious when shading and night-purge ventilation were applied (Figure 6-12). In the studied climate for Mandalay, when the studied models were impossible to provide thermal comfort through passive cooling, the MVHR summer bypass could be an option. On the other hand, in climates with mild winters and cool summers (a mild maritime climate of the UK), the use of MVHR could be omitted without compromising comfort levels, achieving at least equivalent energy savings resulting from adopting the Passivhaus model (Sassi, 2013). This suggests that any ultra-low energy building model, Passivhaus or naturally ventilated, will require some basic understanding to ensure optimal operation. Particularly for the tropical climate, when active ventilation is introduced, removing the humid air is critical, for which integrating dehumidification to the MVHR will play a role for 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, p26). 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. Therefore, future studies should explore a full package of Passivhaus for the tropical climate, both from natural ventilation and active ventilation design.

6.1.7 Findings

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; the results of Figure 6-4 revealed that the Passivhaus standard is applicable in Myanmar climate following its steady-state calculation with mechanical ventilation. The impacts of free-running mode on Passivhaus building envelopes, which were not included in the PHPP calculation, 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 range. By using IESVE, Mandalay, a tropical climate city in Myanmar, was chosen to test the hypothesis. According to the findings discussed in the previous sections, the research questions of this study can be answered.

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 which 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 for construction materials (Figure 6-2); 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 controlling heat transfer, infiltration, and leakage heat transmission, applying mechanical ventilation simultaneously. In this way, a Passivhaus building keeps the desirable thermal comfort consistently. 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. This lack of overheating benchmark and thermal neutrality for the studied climate and cultural context are to be addressed in a future study. Further study is necessary to investigate the window opening behaviour of Myanmar housing in terms of climatic elements and cultural factors. This simulation study presented here was 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. The results of the IESVE simulation were not able to generate detailed calculation for shading effects as the PHPP provides (Figure 6-4). 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.

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 6-12) if 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 finding is aligned to the study of the Brazillian Passivhaus for the tropical climate where the insulated envelope starts to be more advantageous if there are extreme temperatures (high or low) (Tubelo, 2016, Tubelo et al., 2018).

The findings of this study revealed that a slightly higher U-value for walls and floors could be more effective for the tropical climate than the very low U-value suggested by the Passivhaus standard for the cold climate; this was for a naturally ventilated condition. The simulation results presented in this study agreed with Table 6-1. Following the Passivhaus standard, if some degree of thermal mass with insulated building envelopes are introduced to 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. The positive effects of shadings will be more obvious when the building envelope has a high thermal mass in tropical climates. Hence, an investigation of the synergistic effects between shading and building envelope design can make the implementation of Passivhaus more feasible as the costs with the envelope can be lower than the typical Passivhaus envelope.

In this study, different results of the 30 scenarios presented the synergistic effects between external shading and several building thermal envelope parameters; 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. Unlike the tropical vernacular materials, a Passivhaus building is designed with a high-performance building envelope. The other effect of their thermal behaviour of buildings in tropical areas is its urban heat island (Wonorahardjo et al., 2019); therefore, careful optimisation is required in selecting both the U-value and thermal capacity of the envelopes. The review presented in this study highlights that there is a need for defining the thermal comfort benchmark and cooling related occupant behaviour analysis for a free-running mode for a Passivhaus building in the tropics. All the results showed that there would require mechanical ventilation in the predefined scenarios, particularly for future climate scenario-2.

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 technology solutions through building fabric and potential hybrid ventilation. The stylized double Gaussian model fitted to the modern-day showed that the human climate niche is projected to move to higher latitudes in unprecedented ways over the coming decades, and the adaptive capacity of Myanmar has been reduced (Xu et al., 2020). Observed global extreme humid heat shows a wet-bulb temperature between 27°C to 31°C for southern Myanmar. The monitored data set of a modern dwelling (Chapter 5) in the studied city also showed that the indoor wet-bulb temperature reached 30°C and a 'danger' heat index threshold was 14.06% of the time in 2019. Mechanical ventilation is likely to be a solution to building cooling for the emergence of heat and humidity(Raymond et al., 2020). As the climates have changed, the use of shading with the Passivhaus approach 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 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.

6.2 Roof material study

The thermal performance of buildings operates on the way the building modifies the indoor thermal environment against the weather outdoor by preventing heat transfer, providing ventilation, and controlling humidity and comfort. The boundary layer heat transfer fundamentally occurs by three agencies: free convection, forced convection, and radiation (Diamant, 1965, p29). The concept of insulation is to isolate a building's thermal environment from the prevailing surrounding thermal context, making an island of elevated heat in cold climates, or a cool oasis in hot climates (Moe, 2014, p4); therefore, adding insulation layers in building envelopes mainly addresses the first two agencies. The degree of insulation is measured by the thermal transmittance or U-value of the building envelope, which depends upon the thermal conductivity of the various layers of materials, together with the boundary heat transfer coefficient at any solid and air interface of the envelope. Unlike insulation, the cool roof concerns the last agency because cool roofs radiate the heat, preventing absorption, by reflecting the incident sunlight (Levinson and Akbari, 2010).

During the day, the sun is a radiator, and buildings are absorbent because solar radiation falling on the surface of a house is partly reflected away and partially absorbed. It is necessary to reduce heat absorption and heat gain from the surface before the heat is transferred through the building. During the night, the building envelope is another radiator, and the sky is a low-temperature environmental heat sink. In order to cool a building by long wave radiation to the night sky, it is essential to purge absorbed heat from daytime and cool the building fabric. Utilising a combination of night-time ventilation, night-time cooling, thermal mass in walls, and cool roofs have long been recognised as potential passive design strategies. All those heat transfer processes heavily rely on building fabric and ventilation design for its related climate.

In the tropic, humidity and cloud are a barrier for the long wave exchange in the atmosphere (Erell, 2007, p264), which causes less efficiency in cooling down the thermal envelope by natural ventilation alone (Hindrichs and Daniels, 2007, p235), unless a huge volume of air change is applied. Natural ventilation with lightweight building envelopes is thus widely used in tropical climates to remove absorbed heat quickly, in contrast to highly insulated buildings for cold climates. Reducing U-value can provide higher insulation against daytime heat gain in hot and humid tropical climates, but it also hinders night-time heat loss. Cool roofs, unlike insulation, minimize solar absorption and maximize thermal emission through the exterior surface finish by increasing the reflectance value (Levinson and Akbari, 2010). The optimum roof solar reflectance varies under different climate contexts (Piselli et al., 2017); a careful design for the material conductivity and material thickness is thus a concern in the cool roof application.

A field case optical measurements study by Berdahl and Bretz (1997) reported that highly absorptive roofs receive surface and ambient air temperatures as high as 50°C, while less absorptive surfaces receive only about 10°C. For this reason, cool coloured roofs are effective in reducing ambient outside air temperature. A parametric analysis done by Synnefa et al. (2007) found that an increase in roof solar reflectance by 0.65 resulting from the application of cool-coating reduced hours of discomfort by 9–100%, and the maximum temperature by 1.2–3.7°C, depending on the climatic conditions. These reductions were found to be more crucial for poorly or non-insulated buildings. However, Saber et al. (2012) showed that white roofs could lead to longer-term moisture-related problems, depending on specific roof systems under particular climate contexts. Garde et al. (2004) also found that differences of more than 3°C were observed between a dwelling with a well-insulated roof and another one with no insulation in the tropical climate of Saint-Pierre, Réunion. Another tropical climate case study in Puerto Rico proved that the roof insulation system could reduce the typical thermal load by over 70%, while efficiently controlling thermal fluctuations (Alvarado and Martinez, 2008). Besides its effectiveness to reduce the heat transfer, for a cold temperate climate, cool roofs are more effective in the summer, but result in an annual energy penalty due to their performance in winter of London, UK; therefore, adding insulation and a cool roof reduces the relative effectiveness of the roofs because its heading demand is high (Virk et al., 2015). Therefore, a careful design is required if the insulation is introduced to the Myanmar climate context.

In tropical climates, a roof performs defensive effects of preventing precipitation and solar gains (Hyde, 2001, p137-138), and resists the destructive effects of heating and cooling cycles (Athienitis and Santamouris, 2002, p6). Roof materials in the majority of Myanmar housing have been changed from a thatched roof to a reflective metal roof to avoid solar heat gain. It is clear that the nature of the climate fundamentally determines material property selection and ventilation design; however, an understanding of the relationship between roof insulation, wall insulation, and ventilation is still a scope to investigate for the Myanmar context. The context of this study is to determine the impacts and the sensitivity of the thermophysical property of the building envelope considering a naturally ventilated condition in tropical climates.

In this study, it was hypothesised that if the roof has a cool roof effect with low solar absorptivity and high thermal emissivity, “the higher the U-value, the better” could overwrite “the lower the U-value, the better,” which is a characteristic of reflective insulation. It was aimed to fill the knowledge gap of understanding the relationship between envelope U-value, roof solar absorptivity and thermal emissivity, and the local climate contexts of Myanmar. In the PHPP program, the exterior absorptivity and emissivity values (as a property of a cool roof) are considered in its 'Areas' worksheet to define building components lists. However, using a dynamic simulation program, a parametric study with sensitivity analysis might be worth investigation as the ventilation effect on the hourly profiles can be reviewed. Therefore, the objective of this study was to investigate the impact of roof insulation and cool roof effect in the Myanmar climates and to review the nocturnal ventilation affect insulated and uninsulated buildings in Myanmar? Using the sensitivity of the thermal performance of the model with varying levels of exterior finish and insulation, coupled with the use of natural ventilation, the feasible options to improve the indoor thermal environment for future climate change scenarios were then discussed based on the findings.

6.2.1 Methodology

Sensitivity analysis was conducted to investigate the influences of the roof surface and envelope insulation in naturally ventilated tropical building models. Technically, a sensitivity analysis is based on the ‘one-factor-at-a-time’ approach, used to assess the relative importance of input factors in the presence of uncertainty factors (Saltelli et al., 2006). The series of results through sensitivity analysis allows checking two outputs: which variables in which range are more decisive than others; and how far the results exceeded the threshold at a given time. In the following section, all known dependent and independent variables were defined to understand the sources of uncertainty and to carry out the sensitivity analysis with dynamic simulations. The same typical weather files used in Section 3.1 were also used in this study.

Regarding the future climate scenarios, six future climate weather files were created by using a “shift” of a current hourly weather data parameter by adding increased values (Jentsch et al., 2008). The values presented in Table 1-1 were used.

U-Value matrix and tested variables: The U-values were chosen in this study by considering two basic construction materials. Generally, 220mm (9 inches) solid brick wall with 13mm thick plaster had the U-value of 2.09 W/m^{2}K, and a waterproof roof was covered with 19mm timber decking, ventilated airspace, vapour control layers, and 12.5mm plasterboard, with the U-value of 2.35 W/m^{2}K (CIBSE, 2007). Based on these assumptions, the highest range was set at 2.0 W/m^{2}K in this study. Each matrix was offset by 0.5, but the lowest range was kept at 0.2 W/m^{2}K, considering Expanded Polystyrene insulation (EPS) insulation. When one U-value of a building system was changed, there were 125 sets of U-value matrix. Considering the solar absorptance (SA or α) and thermal emittance (TE or ε) variables for cool roof function, higher and lower values were introduced. By theory, SA becomes 1 if a surface is black opaque, while TE becomes 1 when a surface emits thermal radiation highly (Coolrooftoolkit, 2012). In this analysis, the high SA and high TE were set as 0.9. The low SA and low TE were set as 0.3. When the U-value was introduced as low as 0.2 W/m^{2}K, it could affect the thermal mass properties. However, it was treated as a constant value for all 125 matrices. Two ventilation modes – daytime ventilation mode and a 24-hour ventilation mode – were considered in this study. Finally, there were eight scenarios with a multivariable function to test the pre-defined 125 matrices, as shown in Figure 6-15, where the green colour represents reducing the roof U-values, the blue colour represents reducing the wall U-values, and the yellow colour represents reducing the floor U-values if the other two building envelope U-values were fixed.

Reference model and simulation process: The IES Virtual Environment software (version 2019 Hotfix1) was used to generate dynamic simulations (IESVE, 2015). A simplified cuboid building with 5m length, 5m width, and 3m height was considered as a reference model to carry out further dynamic simulation tasks. The 2m width and 1.125m height south-facing window were considered for the ventilation purpose, with the day-time ventilation mode considered from 06:00 to 18:00. As regards the internal heat gain, one fluorescent lighting with 15 W/m^2 maximum sensible gains from 18:00 to 06:00 was added. Three occupants with 75 W/m^2 maximum sensible gains and 55 W/m^2 latent gain were added for a 24-hour profile. The infiltration rate of 0.5 ach and a ventilation rate of 0.5 ach were added. In the first set of simulations, the defined 125 model simulation matrices had constant geometry, internal gains, infiltration, glazing, fenestration, and thermal mass, but the U-values of the roof, walls, and floor varied. The finish of the surfaces for each scenario was also fixed, meaning that absorptivity and emissivity were also constant. The simulation was then run for two ventilation modes. In the next set of simulations, absorptivity and emissivity were varied following the pre-defined eight scenarios. Each of the simulations was run in three cities to understand the sensitivity of the model to these parameters in each climate.

U-value variation from 2.0W/m2K to 0.2W/m2K. [R=roof, W=wall, F=floor]

R2.0_W0.2_F0.2	R1.5_W0.2_F0.2	R1.0_W0.2_F0.2	R0.5_W0.2_F0.2	R0.2_W0.2_F0.2
R2.0_W0.5_F0.2	R1.5_W0.5_F0.2	R1.0_W0.5_F0.2	R0.5_W0.5_F0.2	R0.2_W0.5_F0.2
R2.0_W1.0_F0.2	R1.5_W1.0_F0.2	R1.0_W1.0_F0.2	R0.5_W1.0_F0.2	R0.2_W1.0_F0.2
R2.0_W1.5_F0.2	R1.5_W1.5_F0.2	R1.0_W1.5_F0.2	R0.5_W1.5_F0.2	R0.2_W1.5_F0.2
R2.0_W2.0_F0.2	R1.5_W2.0_F0.2	R1.0_W2.0_F0.2	R0.5_W2.0_F0.2	R0.2_W2.0_F0.2
R2.0_W0.2_F0.5	R1.5_W0.2_F0.5	R1.0_W0.2_F0.5	R0.5_W0.2_F0.5	R0.2_W0.2_F0.5
R2.0_W0.5_F0.5	R1.5_W0.5_F0.5	R1.0_W0.5_F0.5	R0.5_W0.5_F0.5	R0.2_W0.5_F0.5
R2.0_W1.0_F0.5	R1.5_W1.0_F0.5	R1.0_W1.0_F0.5	R0.5_W1.0_F0.5	R0.2_W1.0_F0.5
R2.0_W1.5_F0.5	R1.5_W1.5_F0.5	R1.0_W1.5_F0.5	R0.5_W1.5_F0.5	R0.2_W1.5_F0.5
R2.0_W2.0_F0.5	R1.5_W2.0_F0.5	R1.0_W2.0_F0.5	R0.5_W2.0_F0.5	R0.2_W2.0_F0.5
R2.0_W0.2_F1.0	R1.5_W0.2_F1.0	R1.0_W0.2_F1.0	R0.5_W0.2_F1.0	R0.2_W0.2_F1.0
R2.0_W0.5_F1.0	R1.5_W0.5_F1.0	R1.0_W0.5_F1.0	R0.5_W0.5_F1.0	R0.2_W0.5_F1.0
R2.0_W1.0_F1.0	R1.5_W1.0_F1.0	R1.0_W1.0_F1.0	R0.5_W1.0_F1.0	R0.2_W1.0_F1.0
R2.0_W1.5_F1.0	R1.5_W1.5_F1.0	R1.0_W1.5_F1.0	R0.5_W1.5_F1.0	R0.2_W1.5_F1.0
R2.0_W2.0_F1.0	R1.5_W2.0_F1.0	R1.0_W2.0_F1.0	R0.5_W2.0_F1.0	R0.2_W2.0_F1.0
R2.0_W0.2_F1.5	R1.5_W0.2_F1.5	R1.0_W0.2_F1.5	R0.5_W0.2_F1.5	R0.2_W0.2_F1.5
R2.0_W0.5_F1.5	R1.5_W0.5_F1.5	R1.0_W0.5_F1.5	R0.5_W0.5_F1.5	R0.2_W0.5_F1.5
R2.0_W1.0_F1.5	R1.5_W1.0_F1.5	R1.0_W1.0_F1.5	R0.5_W1.0_F1.5	R0.2_W1.0_F1.5
R2.0_W1.5_F1.5	R1.5_W1.5_F1.5	R1.0_W1.5_F1.5	R0.5_W1.5_F1.5	R0.2_W1.5_F1.5
R2.0_W2.0_F1.5	R1.5_W2.0_F1.5	R1.0_W2.0_F1.5	R0.5_W2.0_F1.5	R0.2_W2.0_F1.5
R2.0_W0.2_F2.0	R1.5_W0.2_F2.0	R1.0_W0.2_F2.0	R0.5_W0.2_F2.0	R0.2_W0.2_F2.0
R2.0_W0.5_F2.0	R1.5_W0.5_F2.0	R1.0_W0.5_F2.0	R0.5_W0.5_F2.0	R0.2_W0.5_F2.0
R2.0_W1.0_F2.0	R1.5_W1.0_F2.0	R1.0_W1.0_F2.0	R0.5_W1.0_F2.0	R0.2_W1.0_F2.0
R2.0_W1.5_F2.0	R1.5_W1.5_F2.0	R1.0_W1.5_F2.0	R0.5_W1.5_F2.0	R0.2_W1.5_F2.0
R2.0_W2.0_F2.0	R1.5_W2.0_F2.0	R1.0_W2.0_F2.0	R0.5_W2.0_F2.0	R0.2_W2.0_F2.0

Each matrix is tested from eight scenarios:
α=0.9, = ε=0.9, Day-time ventilation mode
α=0.9, = ε=0.3, Day-time ventilation mode
α=0.3, = ε=0.9, Day-time ventilation mode
α=0.3, = ε=0.3, Day-time ventilation mode

α=0.9, = ε=0.9, 24 hours ventilation mode
α=0.9, = ε=0.3, 24 hours ventilation mode
α=0.3, = ε=0.9, 24 hours ventilation mode
α=0.3, = ε=0.3, 24 hours ventilation mode

α and ε variables are only varied for roof.

All matrices are tested for three cities: Yangon, Mandalay, and Myitkyina

The results of highlighted coloured matrices are shown in the charts.

Reduced u-value from roof
Reduced u-value from wall
Reduced u-value from floor

Reference Model

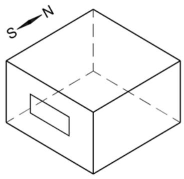


Figure 6-15. Matrix table for 125 U-value variation of roof, wall, and floor

***Output parameters and comparison target*:** The results of sensitivity analyses were carried out to evaluate the impact of material variables on the thermally comfortable indoor environment. The output data was concerned to check the range that exceeded a threshold of comfortable temperature and the peak condition reached in each scenario. In this study, the concern was the impacts of thermophysical properties for indoor environments. The human factor was not a key performance indicator here. On the other hand, the adaptable temperature can be varied by the influences of local climate contexts, building types, diverse cultural backgrounds, and so forth. For the sake of convenience in this study, a range from 24°C to 36°C was considered to check as a threshold and to generate quantitative results. Intervals of 4°C were used (i.e., 24°C, 28°C, 32°C, and 36°C), with an acceptable condition threshold of 32°C (above which overheating occurs). Temperatures above 36°C were considered to be in the extreme range. It is important to note that the range here was for comparison purposes, and it was not defined as a thermal comfort benchmark for the study climates.

6.2.2 Simulation results

The results of the simulation matrix were then generated through the defined level of insulation and roof exterior finishes. The hourly temperature results were extracted to check the sensitivities of material variables to indoor air temperature (AT), mean radiant temperature (MRT), and the internal surface temperature of the roof. Note that the percentage of a year in the results was defined as the percentage of the annual hours of a year, which was 8760 hours for 100%.

The sensitivity of insulation location: In Figure 6-16, the results of Yangon were presented for eight scenarios by using the 32°C thresholds. A very similar result was found in the other two cities, although the results were not presented here. The results proved that the logical understanding of adding insulation to the roof at first was the best case. The peak temperatures were found in α=0.9 and ε=0.3 scenario, which was opposed to the cool roof variable. Impressive results were found in α = 0.3 and ε = 0.9 scenarios, where overheating hours were increased when the U-values were reduced. This means that if a roof had a cool roof performance, a low U-value was undesirable. The results clearly showed that reducing U-values was more effective if a roof had high SA and high TE. Similar impressive results could be seen in two cases: the R0.2_W2.0_F2.0 matrix with high SA, and the R2.0_W2.0_F2.0 matrix with low SA. In a roof with a very low U-value, the internal room temperatures were increased when the wall U-values were reduced in the daytime-only ventilation mode. This means that as long as a building was protected from the solar heat gain by the roof, wall insulation was not required in Myanmar. The results were worse if the floor U-value was reduced. Understandably, the passive approach of ground cooling was lost when the floor U-value was reduced. An impressive result was that the sensitivity of 125 U-value matrices had less difference in the 24-hour ventilation; regardless of the roof exterior finish variation, the intensity of overheat could reduce effectively. Based on the first 3000 simulation results, 13 sets of the optimum and considerable U-value matrices were selected for further investigation. The selected matrices were highlighted in Figure 6-15, where the feasible options were highlighted in green, blue, and yellow colour, in which the green colour was for priority consideration. The unlighted colours represent unfeasible options to consider, as overheating periods were extended when the U-values were reduced.

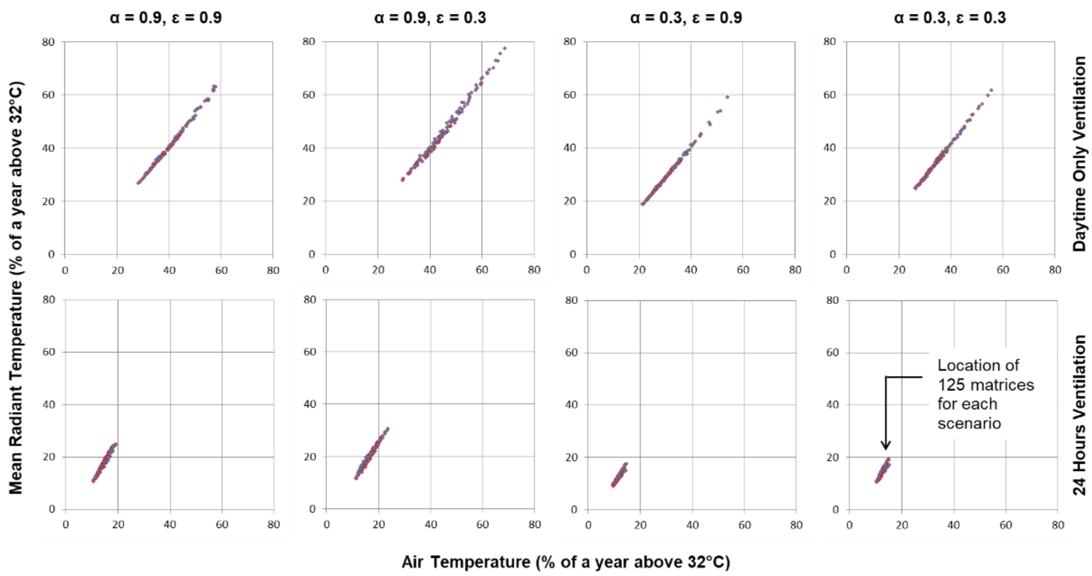


Figure 6-16. Percentage of the annual hours above 32°C for eight scenarios in Yangon

The sensitivity of U-value, solar absorptivity, and thermal emissivity: This section presents the temperature ranges of the exterior condition and eight scenarios of indoor room temperature. Since it was known that reducing the roof U-value was the most efficient approach, five U-value matrices were selected for comparison here: R2.0_W2.0_F2.0, R1.5_W2.0_F2.0, R1.0_W2.0_F2.0, R0.5_W2.0_F2.0, and R0.2_W2.0_F2.0. Among all results, Mandalay received the longest overheating period; for example, 13.95% of the annual hours were above 36°C, dropping to 8.53% of the annual hours if the roof U-value was reduced from 2 W/m^{2}K to 0.2 W/m^{2}K in α=0.9 and ε=0.9 scenario. Only 3.82% of the annual hours were above 36°C in the typical weather file of Mandalay. In Mandalay, 18.21% of the annual hours were above 36°C, which dropped to 9.10% of the annual hours if the roof U-value was reduced from 2 W/m^{2}K to 0.2 W/m^{2}K in α=0.9 and ε=0.3 scenario. This means that reducing the U-value was more sensitive in low emissivity cases. However, high emissivity cases yielded better results. In the scenario with α = 0.9 and ε = 0.9 in the daytime ventilation mode, the overheating period above 32°C was decreased by 5.18%, 2.75%, and 6.89% of the annual hours in Yangon, Mandalay, and Myitkyina (respectively) when the roof U-value was reduced from 2.0 to 0.2W/m^{2}K. A very similar result could be found in a 24-hour ventilation mode without reducing the roof U-value from 2 W/m^{2}K, which means a 24-hour ventilation model could decrease overheating hours more than reducing the U-value. As shown in Figure 6-17, the effect of the insulation of a roof surface on U-value reduction was only effective in non-cool roof conditions. Once the roof surface was considered as a cool roof, the changes of interior room air temperature were insignificant and even bring worse overheating risks associated with reducing the U-value. The impact of overheating from annual results and hottest day temperature fluctuation for the selected five U-value matrices are presented in Figure 6-18 and Figure 6-19.

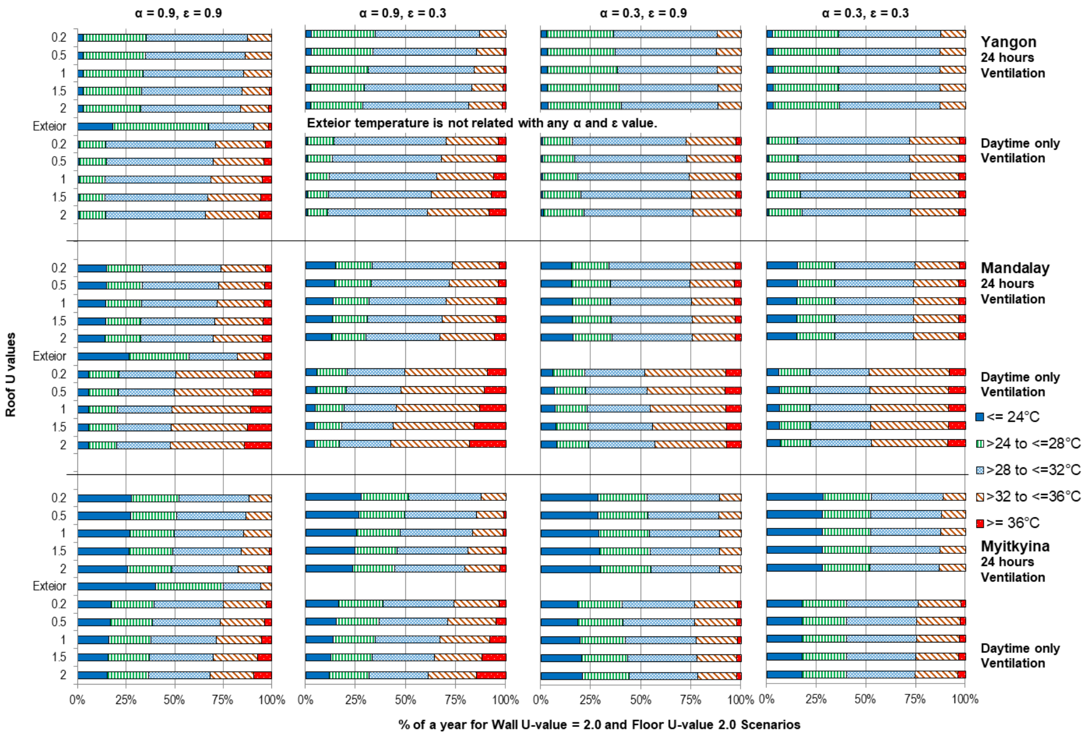


Figure 6-17. Room air temperature contributes to the percentage of the annual hours in a typical weather year for three cities with a fixed wall and floor u-value cases

The sensitivity to internal roof surface temperature and mean radiant temperature: Figure 6-18 presents the results of 13 U-value matrices for the room air temperature and roof internal surface temperature above 32°C for the three cities. The internal roof surface received a higher temperature than the temperature of the air mass below. There was a shorter period of extreme overheating above 36°C in α=0.3 and ε=0.9 scenario in Figure 6-17, but there were unremarkable differences in reducing U-value. It can be seen in Figure 6-18 that divergent chart results were found in the cases with α = 0.9 and ε = 0.3 and α = 0.3 and ε = 0.9 while the roof U-values were varied. On the other hand, the overheating period was extended when the wall and floor U-values were reduced in low SA daytime ventilation cases. Figure 6-18 clearly shows the importance of the surface colouration of exterior walls and roof, and the necessity of maintaining ground cooling without reducing floor U-value. The temperatures could be reduced effectively when nocturnal ventilation was applied; for example, 27.16% of the annual hours reduction could be found in Mandalay R0.2_W2.0_F2.0 cases.

The relationship between the air temperature (AT) and the mean radiant temperature (MRT) for the hottest day of Myitkyina is presented in Figure 6-19 for five U-value matrices. Very similar results were found for the other two cities, but Myitkyina received the highest and worst temperature for the hottest day of the year due to its low wind speed throughout the year. Consistent trend lines were found for all cases, but the significant difference was between the values of exterior roof surfaces rather than U-values. The effort of reducing U-values had less impact on the AT, but hugely affected the MRT, especially if the roof had high SA. Although Myitkyina had a shorter period of extreme overheating above 36°C, and the hottest day external air temperature was only 33.34°C, the AT was increased up to 41.38°C, and MRT was increased up to 42.2°C in α = 0.9 and ε = 0.3 when the roof had U-value 2 W/m^{2}K. On the other hand, there were remarkable differences in reducing U-value in low SA cases. Based on the results, it can be stated that the cool roof effect with low SA can give better performance for the hottest day and summertime. This also means that the radiative and convective heat transfer was more sensitive in the study climate rather than conductive heat transfer.

Comparison for the typical weather year and future climate change scenarios: Figure 6-20 compares overheating hours above 36°C for three cases, comprising a typical weather year and two future climate scenarios. The worst results were found in 2.7°C DBT annually in increased cases. If 1.3°C DBT annually increased cases and 29°C DBT increased in summer cases were compared, a small difference was found in Mandalay and Myitkyina, but there was a significant difference in Yangon, especially in α=0.3 with ε=0.9 scenario. Technically, the air in Yangon contained more vapour due to its location near the ocean. Intrinsically high humidity and increasing global temperatures compound the summer overheating risk in Yangon.

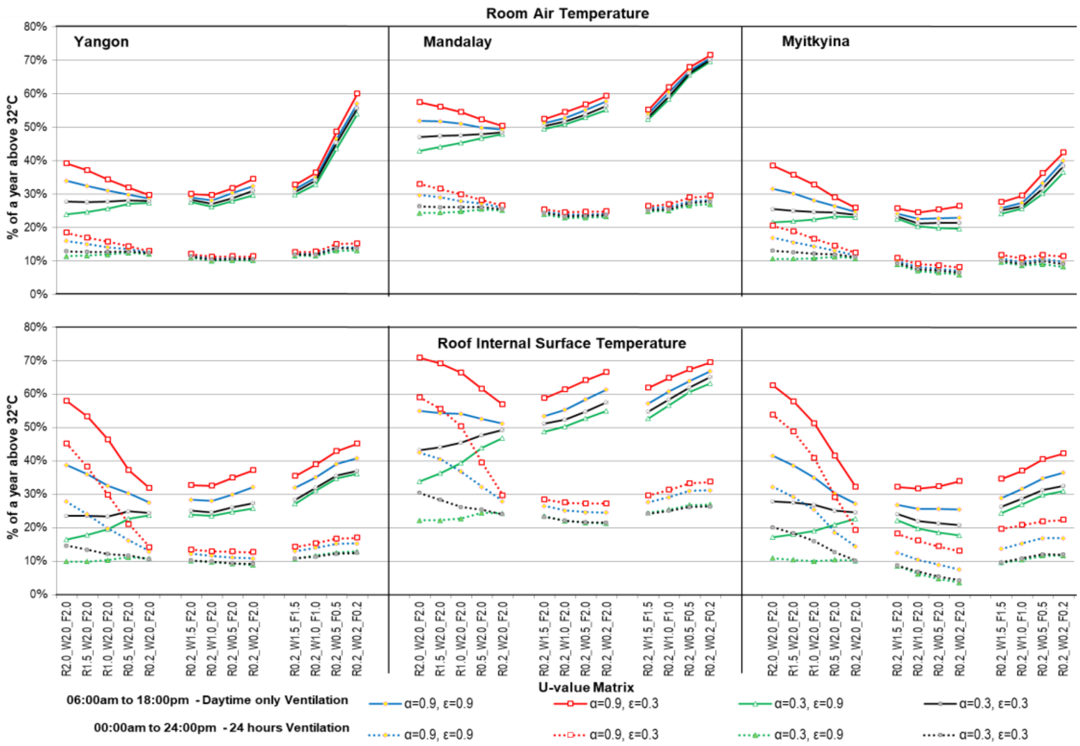


Figure 6-18. Room air and roof internal surface temperature contributes to the percentage of the annual hours above 32°C in a typical weather year

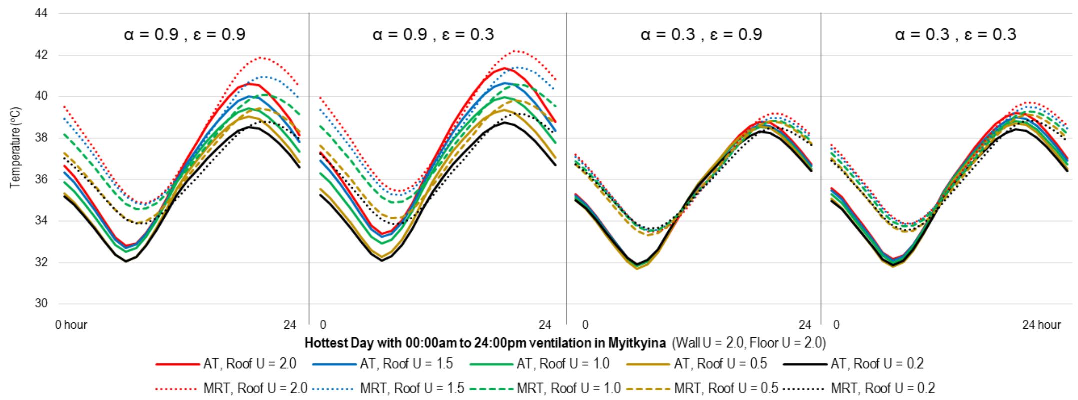


Figure 6-19. Comparison of the hottest day air temperature and mean radiant temperature in a typical weather year

This highlights the importance of design for overheating risks for future climate scenarios. From all the findings, the nocturnal ventilation was more sensitive in the high SA scenario coupled with the roof U-value of 2.0 W/m^{2}K, and more overheating hours could decrease. Although the roof had a low U-value in the high SA scenario, some heat was transferred to the internal environment through daytime ventilation. The nocturnal ventilation has more sensitivity in the TE at night, rather than the values of SA. Therefore, slightly more overheating could be reduced in the α=0.3 with ε=0.9 scenario than in the α=0.3 with ε=0.3 scenario. Nonetheless, the nocturnal ventilation became more sensitive to both high SA and low SA scenarios in future climate scenarios.

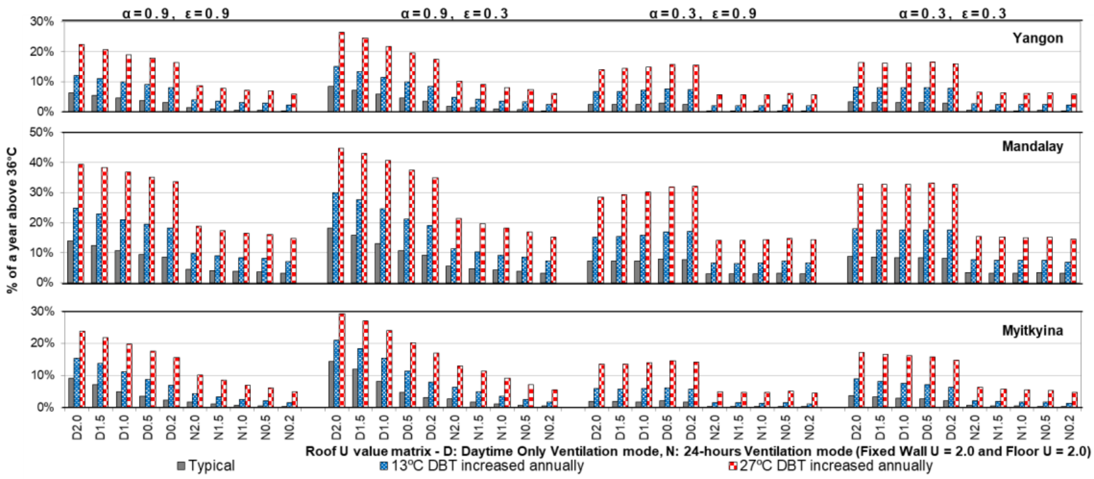


Figure 6-20 Comparison of the overheating hours above 36°C in the typical weather year, 1.3°C DBT annually increased cases, 2.7°C DBT annually increased cases

6.2.3 Discussion

The results of 125 U-value matrices showed that the roof insulation was the paramount feature to consider in high SA scenarios in Myanmar climates. The roof U-value up to 0.2W/m^{2}K, and the wall and floor U-value up to 2.0W/m^{2}K can be optimum values in the defined model. The optimum values can also vary due to building types and sizes. It was necessary to separate two perspectives to answer the question: insulation in the building member and cool roof, which had different roles and impacts. It was obvious that the roof insulation was crucial in the non-cool roof scenarios in the studied climates. The insulation is not a priority approach for Myanmar contexts due to issues of building weight and size, considering its earthquake risks. Technically, preventing heat gain through the exterior surface is more important for the Myanmar contexts, as the predominant heat transfer mode is radiative in the study climates. Whatever the TE, the low SA is the priority to consider, as it can reduce the building's self-weight and approach earthquake resistance with lightweight roofs rather than massive insulated buildings. In the low SA scenario, U-values must be controlled, meaning the insulation should not be a reason to extend the overheating period. Whatever the SA, the high TE was the priority to consider increased radiative heat transfer through the solid roof surface at night, to remove the hot air effectively. On the other hand, moisture-related problems in the white roof and trapped rains on the roof must be solved in the high TE scenarios, as water holds heat, and the white colour envelope demands higher maintenance requirements. When the roof had high SA and high TE, a lower U-value was preferable, which was particularly seen in the results of Myitkyina.

For a tropical climate, cool roofs can be an effective solution throughout the year except for a concern of a short winter period with small amounts of heating loads. In the study climates, the radiative and convective heat transfer processes were the main heat transfer process related to the hot and humid air mass, which called for natural ventilation design to play a critical role. Whatever SA, TE, and roof U-values, nocturnal ventilation was effective to reduce overheating hours, and performance depended on the amount of heat stored in the daytime, the degree of envelope insulation, and the adjacent conditions related to heat transfer at night. For instance, if the envelope was highly insulated, a quick way to transfer heat to the sky was through ventilation only. Less insulated envelopes can facilitate a quicker heat transfer at night. Furthermore, there were benefits in reducing the self-weight of insulation for Myanmar buildings which requires an earthquake resistance design.

6.2.4 Findings

The results of all scenarios showed that coupling the nocturnal ventilation could maximally reduce the overheating period. In this study, all models were considered south facing, but the airspeed of southwest and northeast was stronger in Myitkyina. The effectiveness of nocturnal ventilation depended on the outdoor airspeed, external temperature fluctuations through the building envelope, and the capacity of the building envelope to store heat, which was challenging to report and model precisely, although the thermal mass values in the 125 U-value matrices were fixed. Although the diurnal temperature swing is small, the nocturnal ventilation strategy has great potential to reduce the daytime stored heat, coupled with two roof types: cool roof without insulation; and high SA and high TE with low U-value in the roof. Unfortunately, both roof types had limited capability in daytime-only ventilation modes for the present climate and future climate change scenarios. Careful design with combined design strategies to achieve effective nocturnal ventilation will be the most feasible option to improve the indoor thermal environment for future climate scenarios. Nonetheless, the fundamental priority will also be reducing daytime heat gain to increase the efficiency of nocturnal ventilation.

This study aimed to fill the knowledge gap of understanding the relationship between envelope U-value, roof solar absorptivity and thermal emissivity in Myanmar climates. The impacts of roof materials variables from different temperature ranges with two ventilation modes were presented using the sensitivity analysis. Although the findings of this study were limited with the scope of work and the threshold, the sensitivity analysis of this study could offer feasible solutions to improve thermal performance both for the present and future climate change scenarios.

The current explanation of the concept of insulation (Moe, 2014) is applicable for the tropical climate to isolate a building in the hot and humid environment if different insulation types are applied carefully. Insulation types can be categorized as resistive insulation, reflective insulation, and capacitive insulation (Roaf et al., 2003, p56). The resistive insulation approach of “the lower the U-value, the better to slow down the flow of heat into the building” is more applicable for the roof in all Myanmar climates if the exterior finish has high solar absorption. In this case, the conductivity of the material is crucial, related to increasing the size and the building weight, which raises challenges for earthquake-resistant structural design. If the roof had a cool roof effect with low solar absorptivity and high thermal emissivity, “the higher the u-value, the better” could overwrite “the lower the u-value, the better,” which was a characteristic of reflective insulation. Therefore, the hypothesis of this section was true. In this case, the surface colouration of roofs and exterior walls were crucial, entailing extra maintenance for the use of high albedo. Moreover, the radiation reflected into the surroundings, and unpleasant glare must be controlled. In any case, the efficiency of the resistive and reflective insulation can be increased if the nocturnal ventilation was considered in the studied climates. It was worth noting the efficacy of nocturnal ventilation concerning the data of future weather files, which were created by adding the predicted temperature without changing other variables. Technically, the humidity of night-time was higher than daytime, which led to different thermal comfort adjustment requirements. If the future weather files were created with changes in temperature and humidity, the results would be different. Capacitive insulation aims to avoid immediate heat transfer by its thermal mass. Thermal mass is critical to determine the time lag of thermal storage, and it is always necessary to check both for the annual overheating reduction and summer overheating condition. The thermal mass value was fixed in this study; therefore, there were no findings for this insulation type. In sum, it is necessary to highlight that it is important to take the impacts of capacitive insulation into account when the resistive insulation and reflective insulation are compared. The capacitive insulation is also a challenge for earthquake-resistant structural design. Additionally, the impact of the position of insulation must be considered, such as cool-walls and heat-emitting-walls, which were not investigated in this study. Finally, it can be suggested that the possibilities to improve the efficacy of natural ventilation should be considered with close attention to effectiveness in particular studied climates. It is worth considering the importance of different insulation effect and ventilation variables for improving thermal environments for all Myanmar climates. Careful design with fenestration and ventilation variables can further improve the indoor thermal environment.

6.3 Conclusion

A literature review presented in Section 2.3 allowed Section 6.1 to develop a hypothesis for tropical Passivhaus buildings in the Myanmar climate contexts, also informed that Passivhaus building envelope material properties with shading can either be of cold climate or tropical climate contexts. Historically, roof shading with lightweight buildings provided passive cooling in naturally ventilated tropical vernacular buildings in Myanmar (Chapter 3). Indeed, external shading unquestionably has substantial impacts in all climate contexts, with numerous potential functional and aesthetic roles to play in addition to the traditional function of avoiding direct solar gain, including in the tropical climate of Myanmar. In Section 6.1, it was found that there were slight differences between the model with shading (E6) and without shading (A1); the model E6 indeed performed better than the model A1. On the contrary, it also revealed that the effect of building envelope material would be more profound in future climate scenarios rather than shading. That means the buildings with light-weight material would be more vulnerable to high outdoor temperatures in the future climate scenario than the buildings with Passivhaus building envelope even both have shading.

Whilst increasing thermal mass and adding more insulation are an approachable design for tropical Passivhaus design for climate change adaptation, the building design of Myanmar housing needs to address the requirements of earthquake-resistant design by reducing building self-weight. Therefore, it was investigated the impact of roof insulation and cool roof effect in the Myanmar climates to understand whether the insulation and building weight can be reduced by considering solar absorptivity and reflectance values. The findings of Section 6.2 indicate that the intuitive method of adding insulation to roofs is more effective than adding insulation in walls and floors. It must be emphasized that the methodology of Section 6.2 was not based on PassivHaus' suggestion of building material properties. Therefore, it was found 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." Further study is necessary to optimise roof material variables for one specific climate context.

Both simulation studies presented in this chapter were based on a simple model, and the use of building envelope materials was partially followed the Passivhaus requirements; therefore, further studies need to investigate the impacts of the Passivhaus building envelope materials for a building scale. Moreover, in the scope of Passivhaus design for the tropical climate context, knowledge of using external shading design must be expanded by investigating the interplay between external shading and several building thermal envelope parameters. Despite the limitations above mentioned, the finding of this study can be demonstrated that the Passivhaus' fabric-first approach is possible to adapt to the present and future Myanmar climates to improve the building thermal performance without the need for energy-hungry means of space conditioning, which is of extreme relevance when the need to mitigate and adapt to climate change is considered. As the climates have changed, the resilience of solar shading and cool roof with the Passivhaus approach would be a suitable adaptation strategy for Myanmar, but to enable this to occur, the lessons learned from the literature must be holistically applied and tested in practice.

Overall, the main hypothesis discussed in the 'Introduction' section can be answered from the hypotheses presented in this chapter. This chapter contributes to – (i) new knowledge and evolution of how the Passivhaus building envelope shows a high level of building thermal performance compared to a typical lightweight, not-insulated building envelope in the Myanmar climates; (ii) understanding of how the building thermal performance of Myanmar buildings can be strengthened and how the earthquake resistance design approach can be integrated by adopting the Passivhaus standard with extensive shading and cool roof, and how the Passivhaus approach can bring both passive technology solutions through building fabric and potential hybrid ventilation (Zune et al., 2018b); (iii) a new knowledge for adopting the Passivhaus fabric-first approach in the tropical climate context, to improve the building thermal performance to cope with climate change impacts on buildings.

The world will not change

and find peace if there is

not a new education.

~ U Thant

The third secretary-general

of the United Nations.

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7. Investigating the Passivhaus' Fabric-first Parameters in Studied Dwellings

Historically, roof shading with lightweight buildings provided passive cooling in naturally ventilated tropical vernacular buildings in Myanmar. However, several questions have been raised whether vernacular practices can deliver the required thermal comfort in the present and future climate scenarios. Therefore, how the use of vernacular materials, layouts, and building forms can provide thermal comfort in Myanmar housing was presented in this thesis based on simulation experiments using simplified cube-shaped models. The vernacular case studies presented in Chapter 3 revealed that the efficacy of passive design techniques would not be sufficient to achieve thermal comfort in Myanmar vernacular houses in the predicted future climate scenario.

According to the literature review, it was hypothesised that slightly higher U-values for walls and floors, which are more likely to suit the tropical climate context, can be sufficient to achieve Passivhaus targets if the synergistic effects between shading and building envelope design were considered. On the contrary, there is a conflict between the Passivhaus hypothesis and the tropical vernacular practices. Therefore, Chapter 6 presented the shading effect and sensitivity of roof material properties in the tropical climate contexts, while the use of building envelope materials was partly considered concerning Passivhaus parameters. The results revealed that the buildings with light-weight material would be more vulnerable to high outdoor temperatures in the future climate scenario than the buildings with Passivhaus building envelope even both have shading. However, increasing insulation and building thermal mass could increase the building weight, which has a challenge if an earthquake-resistant design was considered for the Myanmar context. The findings of Chapter 6 also indicated that the intuitive method of adding insulation to roofs is more effective than adding insulation in walls and floors; at the same time, it was found 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.”

As the findings of Chapters 3 and 6 answered a range of research questions based on simulation experiments with cube-shaped models, there is a question left to be answered, is the Passivhauas' fabric first approach is adaptable in real-world buildings in Myanmar? This chapter was attempted to respond to this query by presenting the comparisons between the results of empirical data sets and simulation experiments of the Passivhaus building envelope study.

Regarding the empirical data sets, the on-site measured data set for the indoor thermal environment (Chapter 4) showed that the vernacular dwellings in Myanmar have a close relation to the outdoor weather; therefore, a prediction can be made that they might face overheating risk and have high vulnerability to extreme events in the future due to the long-term climate risk index. On the other hand, the empirical evidence (Chapter 5) also showed that free-running (modern) dwellings in Myanmar face two fundamental challenges for thermal comfort: high vulnerability to extreme heatwave events and underperformance for increased heat index temperature. In order to improve the building thermal performance of those studied dwellings from Chapters 4 and 5, the same hypothesis from Chapter 6 was adapted in this chapter and set to investigate the application of the Passivhaus fabric-first approach in Myanmar to improve the building envelope thermal performance of studied dwellings. Note that the hypothesis tested in this chapter was aimed to support the main hypothesis discussed in the 'Introduction' section.

The Passivhaus standard is considered to be an ultra-low energy building performance standard giving high thermal comfort in buildings. Despite very limited Passivhaus case studies in tropical climate contexts (in Brazil, Indonesia, and Thailand), the Passivhaus concept remains a wholly new approach for Myanmar, which could face several challenges in both design and construction. This chapter was aimed to address such challenges in terms of building thermal performance aspects. The central issue of concern in this chapter was to investigate whether the Passivhaus concept is adaptable in tropical climates in terms of methodological differences between the fabric-first approach building envelope and tropical vernacular construction practices, and the following research questions (RQ 11 and RQ12 of the thesis' research questions) were set to answer.

- How does the Passivhaus' fabric-first building envelope approach perform differently according to the climate differences in Myanmar?
- What are the challenges of adopting the Passivhaus' fabric-first approach in Myanmar in terms of its original context, climate, and methodology differences?

7.1 Methodology

The "case study research method with multiple cases" was utilised to investigate an experiential Passivhaus concept in the tropical climate with different combinations of data sets, including evidence of on-site measurement data sets, simulation validation and simulation prediction. This method allows the evaluation of different sources of information to test concepts on the basis that a consensus of the findings will yield more robust results (Proverbs and Gameson, 2008, p99). The method was established from multiple sources of evidence. The empirical data sets from Chapters 4 and 5 underpin the thrust of this investigation; the simulated data sets from these two chapters can affect the depth of the present study and, to some extent, the validity of the research findings. Comparison of two empirical data sets for distinct outdoor climate and monitored indoor thermal environment data sets reinforces the advantage to compare and contrast findings from a similar or related case. Furthermore, a new simulated data set for Passivhaus fabric-first parameters was introduced in this study. Therefore, the method seeks to provide the meaning of the Passivhaus fabric-first concept in the tropical climate context, and the results can contribute to an in-depth understanding of the central issues being investigated.

Case studies buildings: The case study buildings, as described in Chapters 4 and 5, were named the Mandalay (MDY) and Myitkyina (MKN) dwellings. In this study, the MDY dwelling represents a modern construction type, and the MKN dwelling represents a vernacular construction type. The experimental investigations used calibrated digital and analogue devices monitoring air temperature, relative humidity, and air velocity and direction for a selected room of both dwellings. The experimental devices were selected based on several criteria, such as measurement range, accuracy, and availability, as shown in Table 7-1. Tinytag data loggers are robust, reliable and cost-effective solutions to monitoring environmental conditions; therefore, they are commercially used in several warehouses for the pharmaceutical manufacturing process and in museums, archives and heritage sites to control the indoor thermal environment and energy-efficient chamber test (Fang et al., 2014, Huebner et al., 2018, Museums + Heritage Advisor, n.d). Netatmo weather stations are commercially recognised for their user-friendly setting and reliable results; likewise, they are also used in academic research to monitor the local meteorological conditions (Le, 2020, Venter et al., 2020). Each instrument was placed in a specific position throughout the study period. During the monitored period, the monitored spaces were continuously occupied. Note that the results of the two monitored data sets from Netatmo and Tinytag were able to validate each other, despite their hourly air temperatures exhibiting discrepancies of up to 0.8°C.

Weather files: The typical weather files for both dwellings' simulations comprised ASHRAE standard data (Huang et al., 2014). For the MDY dwelling, the historical weather file for 2019 was generated based on the monitored outdoor data set. Two future weather files (used in Chapter 5) for the MDY dwelling were created: future weather file-1 was based on the standard typical weather year from ASHRAE, and future weather file-2 was based on the monitored year 2019. Note that the diurnal temperature variations of the future weather file-2 were affected by UHI due to the database used for the monitored dwelling being in the urban area of Mandalay. For the MKN dwelling, the historical weather file for 2018 is from ASHRAE, and the future weather file created for this study was based on the standard typical weather year, also used in Chapter 4. Detailed information on the future weather file is presented in Chapters 4 and 5.

Table 7-1. Instruments used in the fieldwork.

Characteristic of dwelling	Instrument	Accuracy, range, resolution	Time
Mandalay (MDY) dwelling in Koppen climate Am			
• Both ground and upper-level wit brick walls and concrete floors, roof covered with zinc sheet. • High-level windows at the backside of the wall allow cross-ventilation. • The entrance is north-facing. • The dwelling is slightly smaller than the Myitkyina dwelling. • Measured parameters: the indoor and outdoor thermal environment data (temperature, relative humidity, and CO2 emissions).	Netatmo weather station (Netatmo, 2019).	• Indoor temperature: accuracy ± 0.3°C, ranges from 0°C to 50°C. • Outdoor temperature: accuracy ± 0.3°C, ranges from: -40°C to 65°C. • Humidity: accuracy: ± 3%, ranges from 0 to 100%. • Carbon dioxide (CO2) meter (indoor): accuracy: ± 50 ppm and ± 5%, ranges from 0 to 5,000 ppm.	01//1/2019 to 31/12/2019 at 30-minute intervals.
• The Tinytag was also installed in the MDY building to verify the accuracy of the Netatmo weather station.	Anemometer	• Wind direction: accuracy: 5°. • Wind speed range: 0 to 45 m/s with 0.5 m/s accuracy.	01//1/2019 to 31/12/2019
Myitkyina (MKN) dwelling in Koppen climate Cwb			
• The ground level has brick walls and concrete floors. • The upper level has timber walls and floors. • The timber frame Dutch gable roof is covered with zinc sheets. • Small gable vents on the pediments of the Dutch roof allow the removal of hot air from the first-floor level rooms. • Measured parameters: the indoor air temperature and indoor relative humidity. • The entrance is north-facing.	Tinytag TGU-4500-Ultra-2 Gemini data logger (Gemini Dataloggers, 2017).	• Temperature range: -25°C to +85°C. • Relative humidity range: 0 to 95%. • Accuracy: ±3%; built-in sensor has a high reading accuracy, and 32,000 reading capacity can be stored.	01/01/2018 - 31/01/2018 at 30-minute intervals.

Simulation models: The simulations were performed using the Integrated Environmental Solution software (IES version 2019 Hotfix1), which was also used in previous chapters. In the simulation, the adjacent houses from the left, right, and back of the monitored dwelling was also modelled; therefore, the external heat gains of the monitored dwelling were decreased due to the shading and sheltering of the adjacent houses. Detailed information on the simulation models is presented in Chapters 4 and 5. The floor plans and perspective views of the simulation models are shown in Figure 7-1. Note that the monitored room of the MDY dwelling was the living room located at the ground level, while the monitored room of the MKN dwelling was the living room located on the upper level.

Material assumptions: Chapters 4 and 5 validate the 'base-case' simulation models for the two dwellings, which were built according to the real-world condition of the case study dwellings. Passivhaus and partially Passivhaus scenarios were introduced in Table 7.2 to compare with the empirical data sets and base case model results. The material assumptions were based on the CIBSE (2015) and IESVE (2015) data sets. In Model A, which was built for the Passivhaus scenario, the material properties of the whole building envelope and the values of infiltration and internal gain complied with Passivhaus criteria. The study presented in Chapter 6 revealed that the hypothesis of a slightly higher U-value for wall and floor could be more effective. Therefore, in the Model B, which was built for partially Passivhaus scenario, the U-value of wall and floor were slightly increased; the value of infiltration was also increased, but the U-value of the roof and the value of internal gain complied with Passivhaus criteria. Both models had the same material properties in the internal wall, internal floor, windows, and door, which complied with Passivhaus criteria. Figure 7-2 presents the sectional details of roof, wall, and floor used in the Passivhaus and partially Passivhaus scenarios.

Figure 7-1. Monitored dwellings in Mandalay and Myitkyina, and the location of monitored rooms

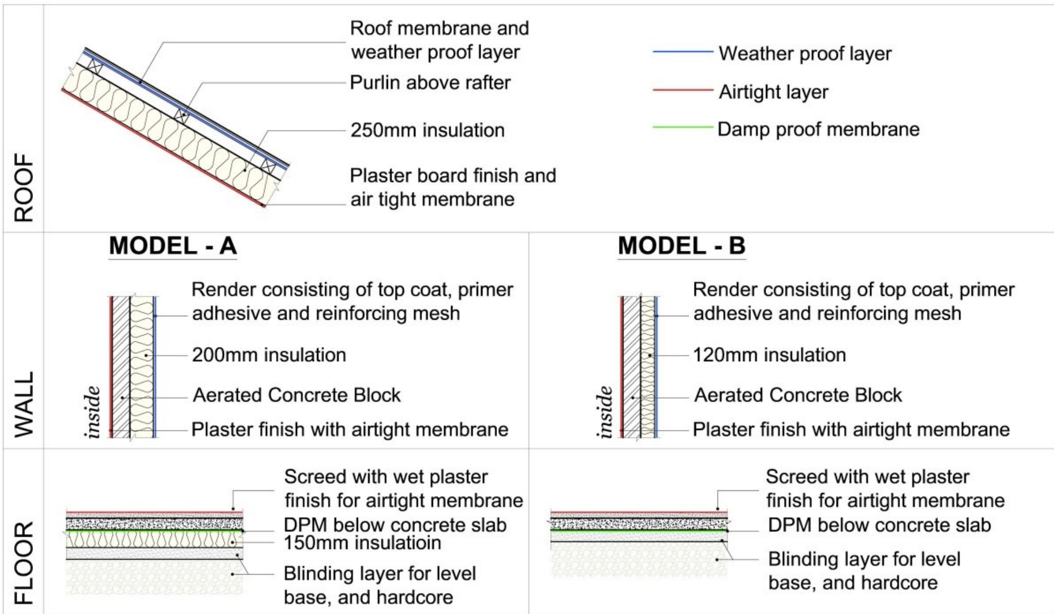

Figure 7-2. Roof, wall, and floor properties in Passivhaus and partially Passivhaus scenarios

Table 7-2. Material assumptions of the Passivhaus and partially Passivhaus scenarios (CIBSE, 2015, IESVE, 2015)

Building envelope configuration	U-value (W/m^2K)	Thermal mass ($kJ/(m^2K)$)	Mass (kg/m^2)	Solar absorptance	Thickness (mm)
Model A: Passivhaus scenario (comply with Passivhaus U-value)					
Roof	0.15	12.0	60.1	0.55	400
Wall (Lightweight)	0.15	72.5	140.8	0.50	380
Floor	0.15	85.0	510.0	0.55	420
Infiltration and internal gain	0.042 ach based on 0.6 ach @ 50Pa, and 2.1 W/m^2				
Model B: Partially Passivhaus scenario (increased U-value at floor and wall, increase infiltration rate)					
Roof	Same as Model A				
Wall (Lightweight)	0.23	72.5	138.8	0.50	300
Floor	1.39	85.0	410.0	0.55	270
Infiltration and internal gain	1 ach and 2.1 W/m^2				
A common material for Models A and B					
Internal floors and wall	Same as the real-world scenarios shown in Chapters 4 and 5.				
Window	Net U = 0.78, Compliant with Passivhaus U-value Opaque glazing windows with aluminium frame. Solar heat gain coefficient = 0.37; Visible light transmittance = 0.76.				
Door	Net U = 0.64, Compliant with Passivhaus U-value.				

Simulation process: Two sets of simulation for the Passivhaus and partially Passivhaus scenarios (Model A and Model B) were performed for two dwellings according to their location, respective weather files, and ventilation scenarios. A ventilation profile for a window to open and close can affect the internal and external temperatures. Opening windows during the daytime is a common practice in Myanmar, regardless of lightweight or non-lightweight building types; therefore, the internal temperatures of naturally ventilated, lightweight buildings in Myanmar are closely reflected by the outdoor climates. In both simulation sets, three ventilation scenarios (V1, V2, and V3) were tested:

- V1: Fully ventilated wit natural ventilation using daytime window opening mode from 06:00 a.m. to 18:00 p.m., which is a common practice in Myanmar.
- V2: Daytime cooling with mechanical ventilation from 10:00 a.m. to 18:00 p.m., and night-purge ventilation using window opening mode from 18:00 p.m. to 06:00 a.m. During the daytime, the windows were closed and the mechanical ventilation for cooling was supplied when the temperature reached above 25°C.
- V3: Mechanical ventilation for the whole year if the temperature reached above 25°C, with the windows closed throughout the whole year.

Comparison method: The simulation set for MDY dwellings contained a total of 16 scenarios, i.e., four weather scenarios (typical, historical 2019, and two future weather files), two scenarios for material assumptions, and two scenarios for window opening profiles. The simulation set for MKN dwellings contained a total of 12 scenarios, i.e., four weather scenarios (typical, historical 2018, and one future weather file), two scenarios for material assumptions, and two scenarios for window opening profiles. The results of the two simulation sets were then compared with the empirical data sets and the base case simulation models. The Passivhaus standard suggests 25°C as a benchmark of overheating temperatures, which could be a challenge for a building with naturally ventilated condition in the tropics. Therefore, the temperature benchmarks were set as 25°C (for Passivhaus standard) and 36°C (for extreme overheating condition). The latter was proposed in this study only for comparison, considering heat stress with extreme caution can occur at 36°C of air temperature with 40% relative humidity (National Weather Service, 2019). The equations of wet-bulb and heat index temperatures utilised to analyse the data that were presented in Chapters 4 and 5.

7.2 Simulation results

This section presents the analysis of two simulation sets for the indoor thermal environment data and their comparison with the empirical datasets and the outdoor weather. The results of indoor air temperature (AT), analysis of overheating risk today (including humidity effect), and analysis of vulnerability to extreme events today based on the wet-bulb temperature (WBT) and heat index temperature (HT) are presented for both dwellings. Note that the percentage of the annual hour in the results was defined as the percentage of the annual hours of a year, which is 8760 hours for 100%.

7.2.1 Mandalay dwelling

Air temperature: First, the air temperature differences between the monitored indoor and simulated data of the Model A with ventilation scenario V1 were checked, from which changes in weather without the effect of the moisture of the air can be obtained. Figure 7-3 shows that the indoor air temperatures of the simulated Model A were consistently above the monitored indoor data set, which was measured for the modern building type in Mandalay. The results reveal that the monitored dwelling had better results. For the historical weather of 2019, the monitored outdoor data set showed that 83.2% of the annual hour was above DBT 25°C, and 6% of the annual hour was above DBT 36°C. In the indoor data set of the monitored dwelling in 2019, 81.6% of the annual hour was above AT 25°C, and 2.9% of the annual hour was above AT 36°C. For the Model A with ventilation scenario V1 in 2019, the simulation results showed that 89.8% of the annual hour was above AT 25°C, and 10% of the annual hour was above AT 36°C. Understandably, the numbers of warmer hours above 36°C in the monitored indoor environment were lower than the weather outdoors, but the number of warmer hours above 36°C in the simulated Model A with ventilation scenario V1 was higher than for the outdoor weather.

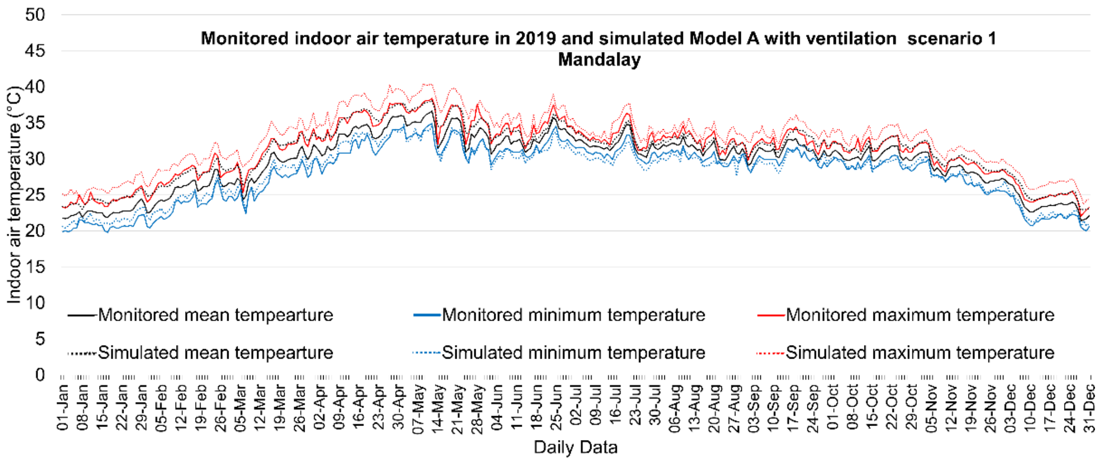

Figure 7-3. Monitored indoor air temperature and simulated air temperatures for the model A with ventilation scenario V1 in 2019, Mandalay dwelling

Figure 7-4 describes the annual values across the whole weather year for different simulation scenarios for the MDY dwelling. The maximum and minimum values with medians and quartiles are clearly visible. The shorter length of quartiles and higher mean and median values were found in 2019 and future climate scenario-2 compared to the typical weather year. The ventilation scenario V1 for both models showed the worst-case scenario, confirming the risk of natural ventilation alone in future climate scenarios. As the ventilation scenario V1 was natural ventilation alone, it was necessary to apply the mechanical ventilation to keep the indoor temperature below AT 25°C in the Models A and B. The value of mean and median temperatures can be significantly reduced using daytime cooling with ventilation scenario V2. The constant indoor AT 25°C was kept in ventilation scenario-3 due to its reliance on mechanical ventilation for the whole year.

In future climate scenario 2, in order to keep the indoor temperature below AT 25°C, mechanical ventilation was required in the Model A for 98.32% of the annual hour and in the Model B for 97.96% of the annual hour. In future climate scenario 2, in order to avoid overheating AT 36°C, mechanical ventilation was required in the Model A for 14.7% of the annual hour and in the Model B for 23.82% of the annual hour. The results revealed that the Model A would need more cooling demand to keep the comfort hours below AT 25°C due to its highly airtight, super-insulated thermal envelope. On the other hand, the Model B would need more cooling demand to avoid the overheating frequency above

AT 36°C. It was also found that the Model A had a higher percentage of the annual hour for the indoor AT above 25°C in a typical weather year, historical weather year 2019 and future climate scenario-1; however, the Model B had higher percentages of the annual hour for the indoor AT above 36°C in both future climate scenarios. The results of the comparison of indoor air temperature 25°C and 36°C revealed that the building envelope with Passivhaus scenario would perform better in reducing peak interior temperatures in the Mandalay climate

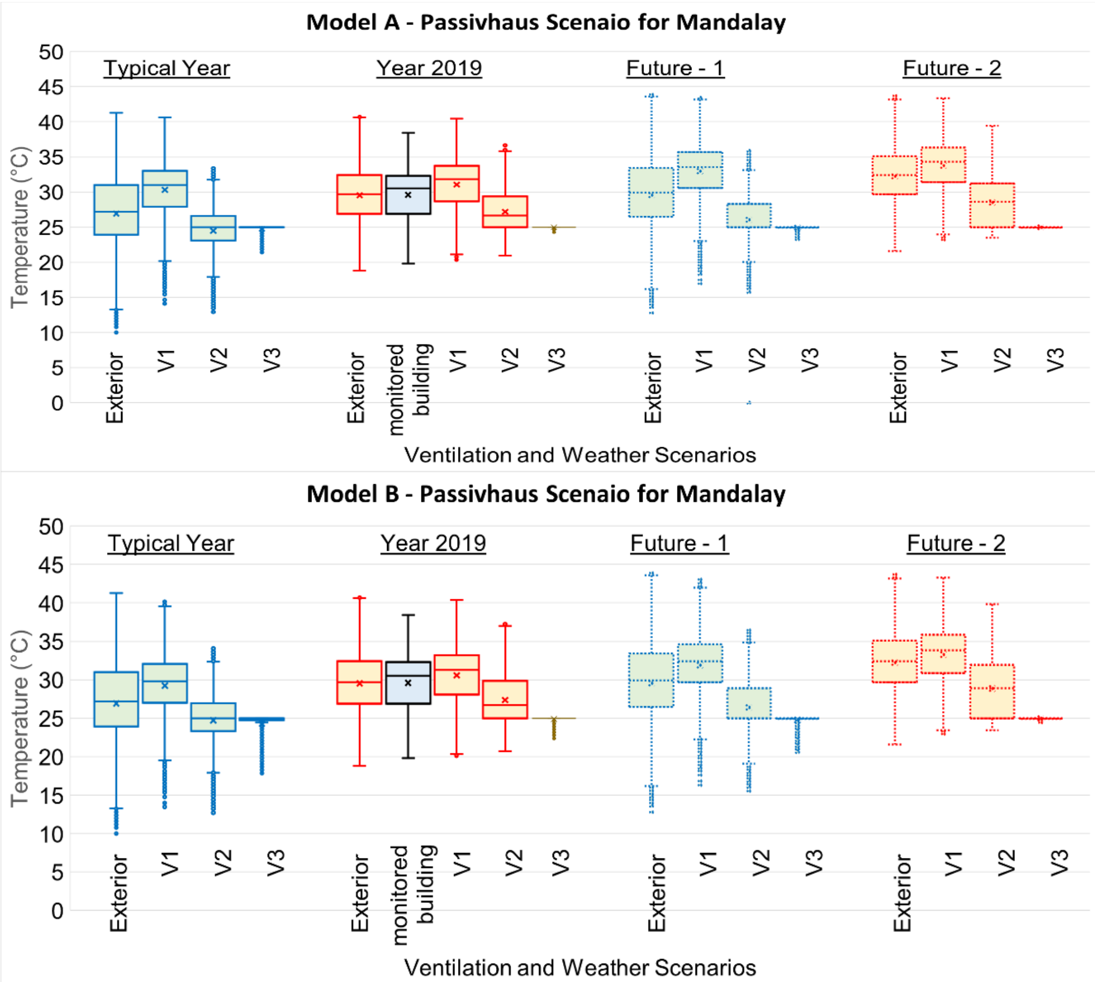

Figure 7-4. Simulated annual air temperatures in Mandalay dwelling (living room) - annual values in box charts.

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CO_2 concentration in the building*:* Figure 7-5 presents the monitored results of the monthly CO_2 concentration level for indoor AT and HT of the Mandalay dwellings in 2019. High indoor air quality for normal background concentration through outdoor ambient air has CO_2 concentration less than 400 ppm, and moderate indoor air quality has outdoor CO_2 concentration of 600-1000 ppm (BSI, 2007). The monitored dwelling was not in the city centre but was located in a neighbourhood close to it.

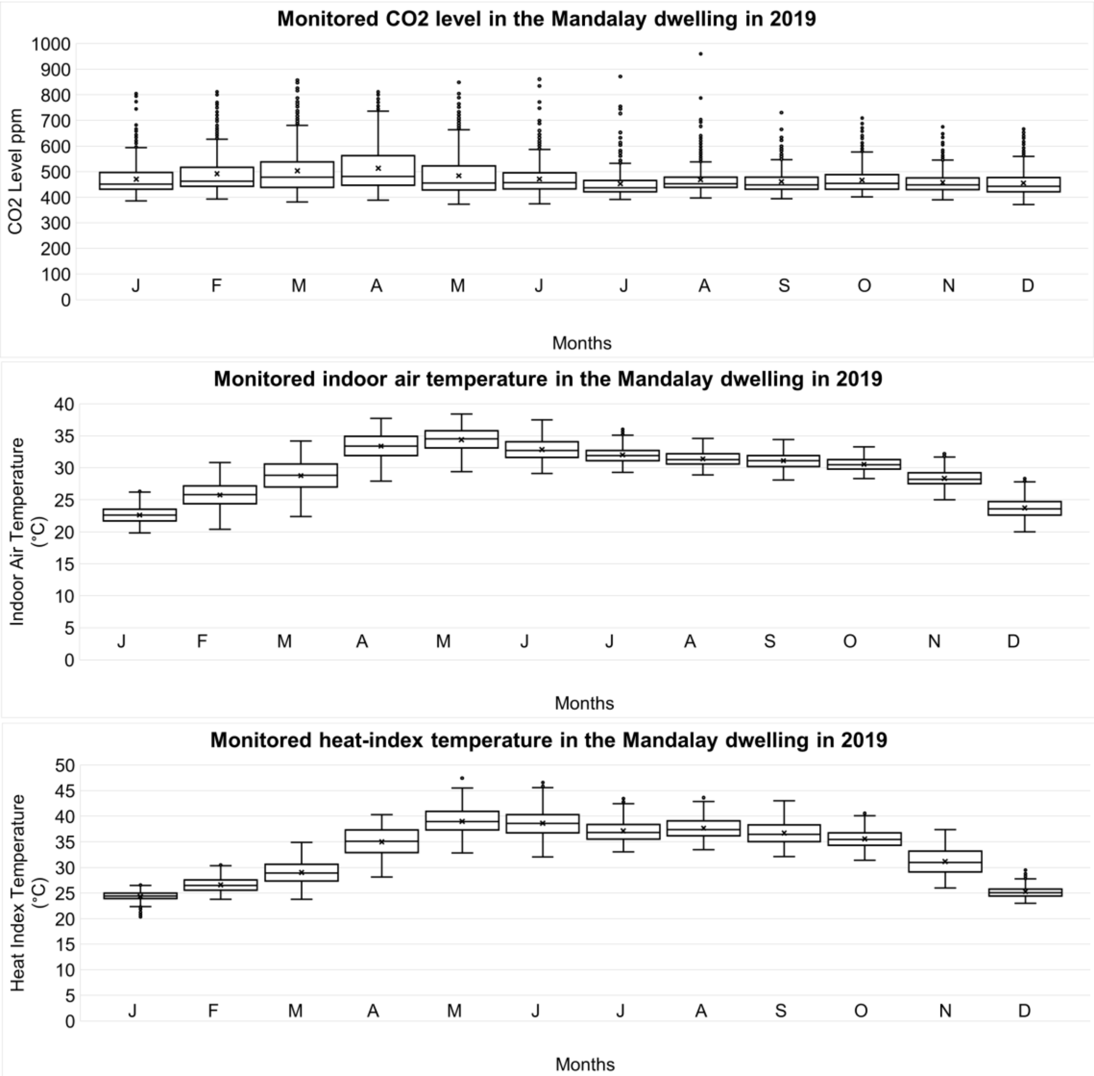

Figure 7-5. Monitored monthly CO_2 level, indoor air temperature and heat index temperature of the Mandalay dwelling in 2019

However, the indoor CO_2 concentration can be affected when the indoor AT increases by means of an airtight, high thermal envelope in the studied climates and if there is no mechanical ventilation. Despite the correlation between AT and HT, it cannot be stated that there is a direct correlation between CO_2 level and indoor air temperature, as the occupants' activity also contributes to indoor CO_2 level. Nevertheless, the monthly results of January to April show that the CO_2 level increased as the indoor AT and outdoor DBT increased. In the simulated models, the internal heat gain and occupant heat gain were considered as Passivhaus' suggestion of 2.1W/m^2; therefore, the CO_2 levels were not obtained from the simulations as people are the main pollution source by measuring the average CO_2 concentration in the building.

Wet-bulb temperatures: Figure 7-6 presents the comparison of WBT in different scenarios. The WBT below 25°C decreased in 2019 and future climate scenarios regardless of model and ventilation scenario differences. In future scenario-1 with ventilation scenario V1, WBT above 30°C accounted for 2.91% of the annual hour in Model A and 6.52% of the annual hour in Model B. In future scenario-2 with ventilation scenario V1, the WBT above 30°C comprised 13.8% of the annual hour in Model A and 9.74% of the annual hour in Model B.

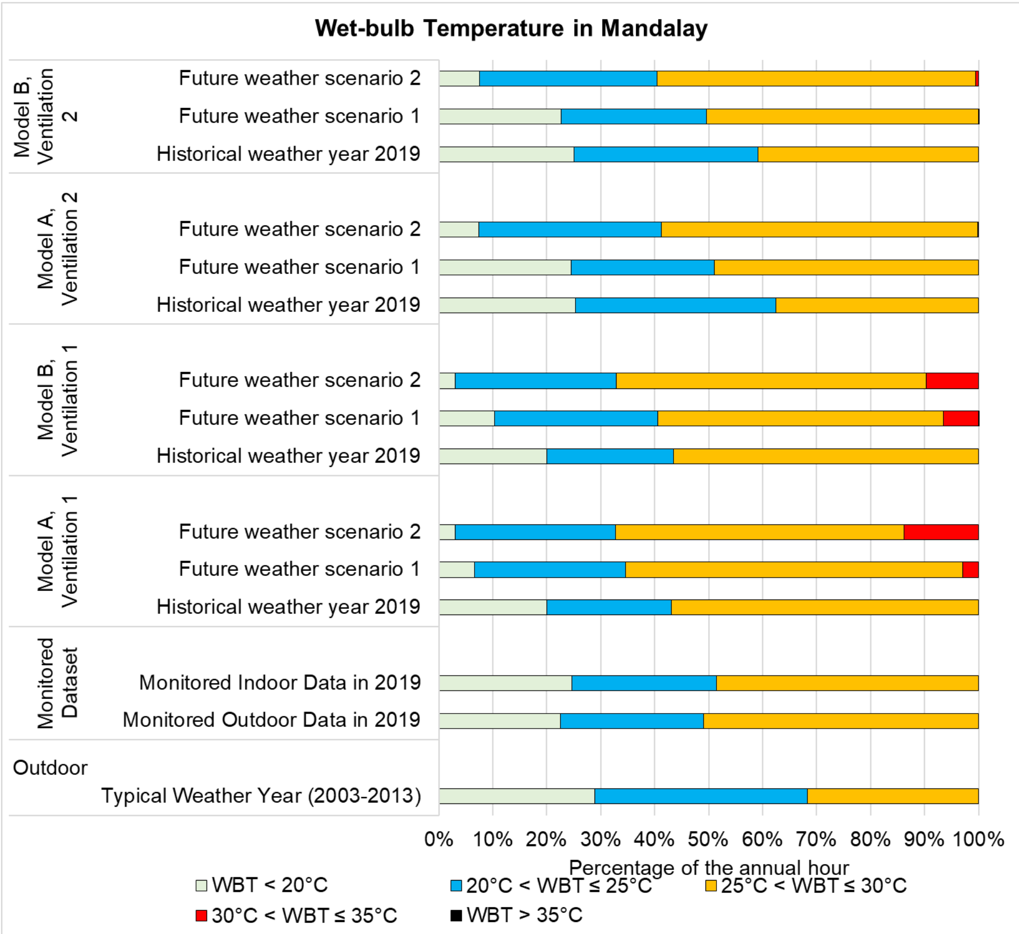

Figure 7-6. Annual wet-bulb temperature in Mandalay in different scenarios

The results showed that Model A maintained a high WBT for a higher percentage of the annual hours than Model B. The models with ventilation scenario V2 keep the WBT below 30°C; this also confirms that natural ventilation alone would bring risks of higher WBT. It was highlighted in Chapter 5 that the WBT below 20°C was decreased in the year 2019 compared to the typical weather year of Mandalay; although the year 2019 was drier than the baseline typical weather year, the effect of relative humidity on WBT was found, due to increased AT both in daytime and night-time conditions.

Heat index temperatures: Figure 7-7 presents the comparison of HT in different scenarios. The HT below 32°C decreased in 2019 and future climate scenarios regardless of model and ventilation scenario differences. In the Model A with ventilation scenario V1, the HT values above 41°C were 24.66%, 51.74%, and 59.19% of the annual hours for the historical weather year 2019, future climate scenario-1, and future climate scenario-2, respectively.

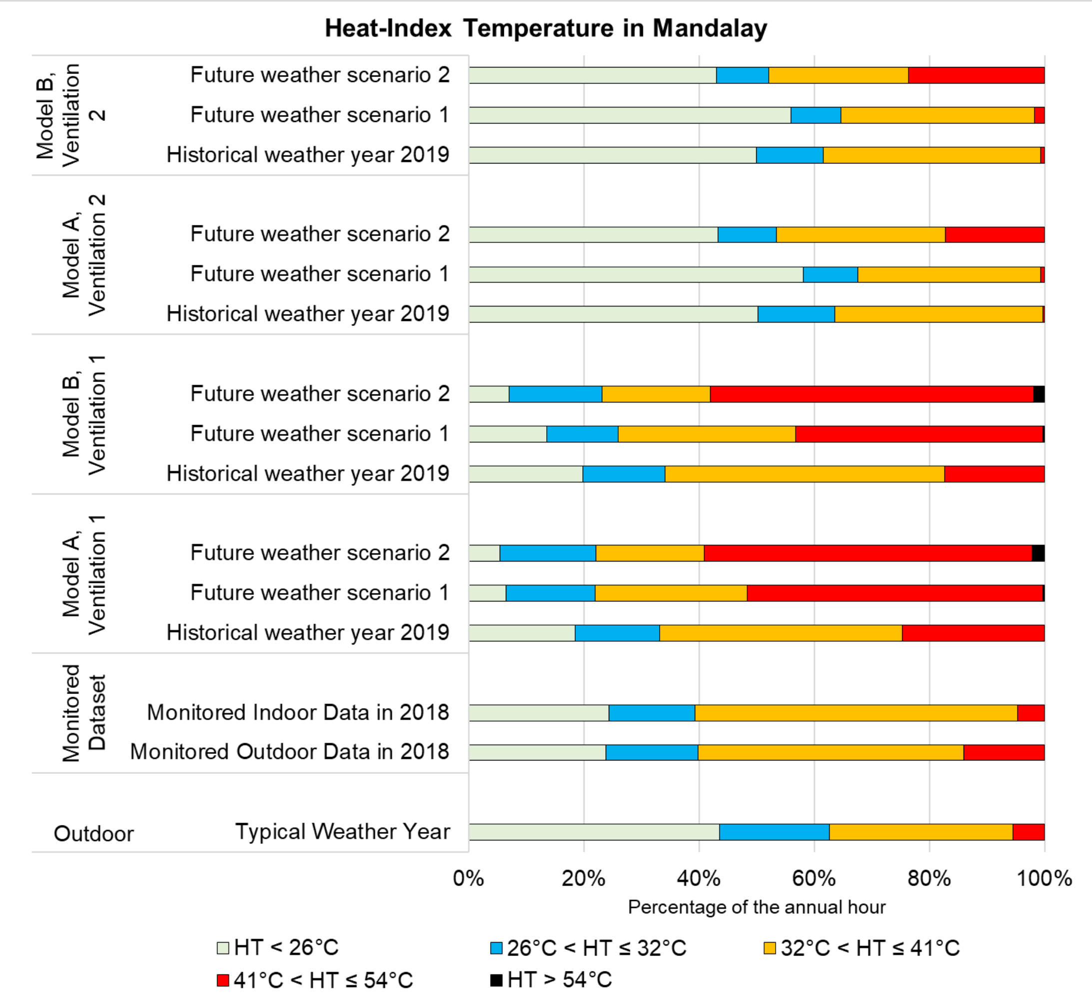

Figure 7-7. Annual heat index temperature in Mandalay in different scenarios

In the Model B with ventilation scenario V1, the HT values above 41°C were 17.36%, 43.29%, and 58.13% of the annual hour for the historical weather year

2019, future climate scenario 1, and future climate scenario 2, respectively. The percentage of the annual hour above HT 41°C was reduced in ventilation scenario V2 due to the daytime cooling from the mechanical ventilation. The results showed that Model A maintained a high HT and WBT for a higher percentage of the annual hour than Model B in the Mandalay climate.

7.2.2 Myitkyina dwelling

Air temperature: First, the air temperature differences between the monitored indoor and simulated data of Model A with ventilation scenario V1 were checked, from which changes in weather without the effect of the moisture of the air can be obtained. Figure 7-8 shows that the indoor air temperatures of the simulated Model A were consistently above the monitored indoor data set, which was measured for the vernacular building type in Myitkyina.

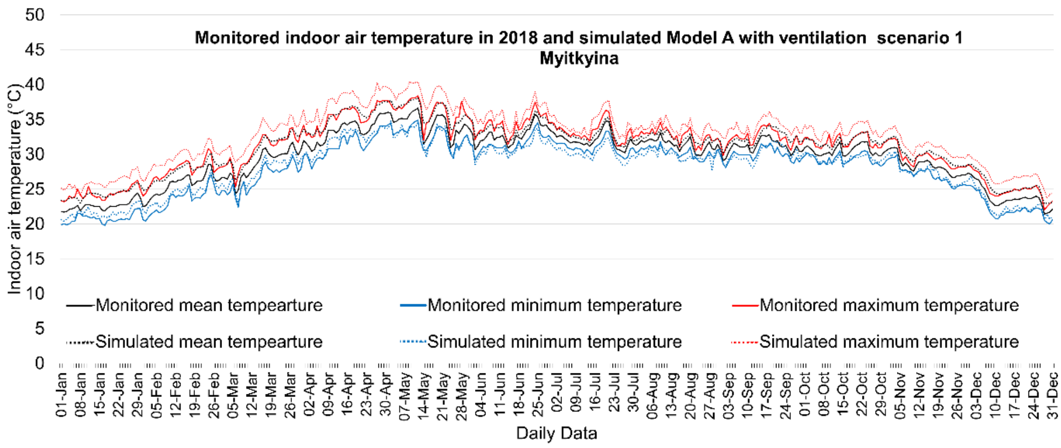

Figure 7-8. Monitored indoor air temperature and simulated air temperatures for the model A with ventilation scenario V1 in 2018, Myitkyina dwelling

For the historical weather 2018, the monitored outdoor data set showed that 61% of the annual hour was above DBT 25°C, and 3.8% of the annual hour was above DBT 36°C. In the indoor data set of the monitored dwelling in 2019, 59.1% of the annual hour was above AT 25°C, and 0.4% of the annual hour was above AT 36°C. In the Model A with ventilation scenario V1 in 2019, the simulation results showed that 57.5% of the annual hour was above AT 25°C, and 1% of the annual hour was above AT 36°C. Understandably, the numbers of warmer hours above AT 36°C in the monitored indoor and the simulated Model A were lower than the weather outdoor, but the simulated Model A (1%)

attained a slightly longer time above AT 36°C than the monitored indoor air temperature (0.4%).

Figure 7-9 also showed that the ventilation scenario V1 for both models was the worst-case scenario for Myitkyina dwelling. Differences between the Models A and B were hard to notice in their annual values through box charts. As the ventilation scenario V1 was natural ventilation alone, it was necessary to apply the mechanical ventilation to keep the indoor temperature below AT 25°C in the Models A and B. In the future climate scenario, to keep the indoor temperature below AT 25°C, mechanical ventilation was required in the Model A for 63.2% of the annual hour and in the Model B for 64.11% of the annual hour. In the future climate scenario, to avoid overheating AT 36°C, mechanical ventilation was required in the Model A for 0.29% of the annual hour and in the Model B for 0.42% of the annual hour.

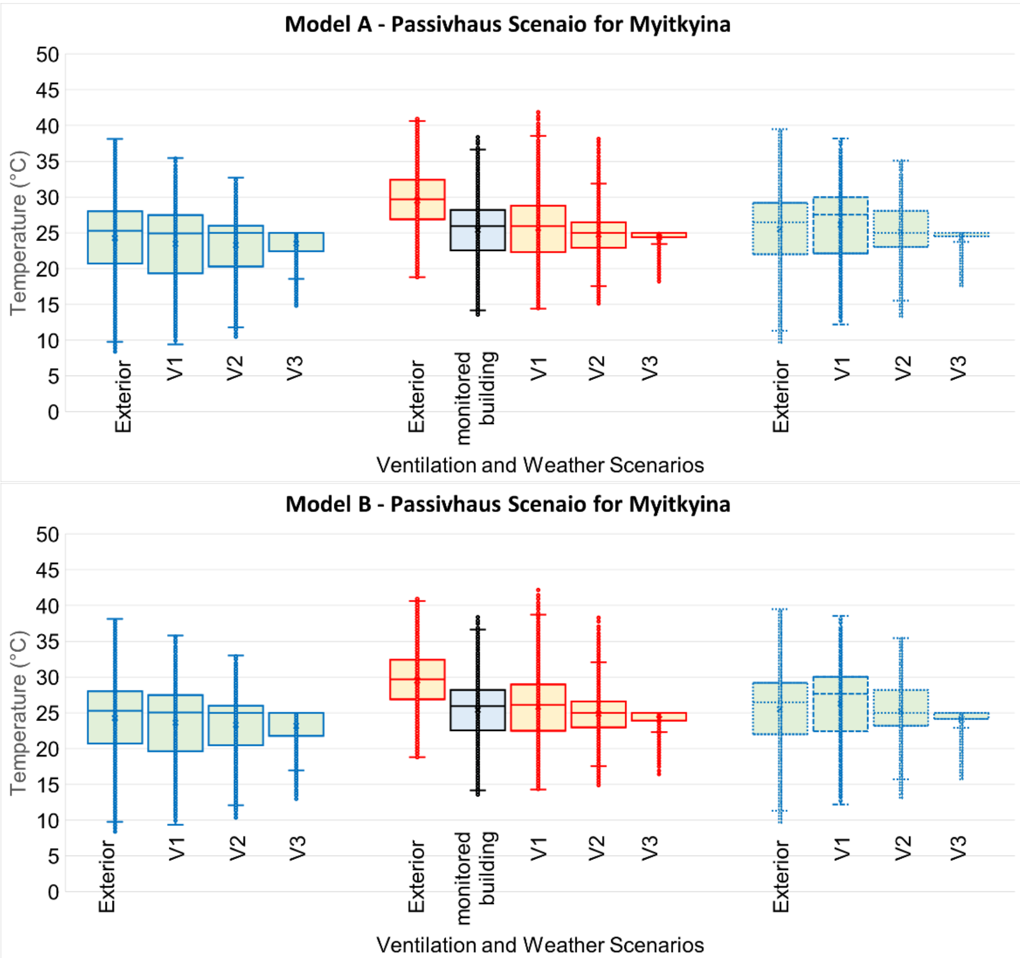

Figure 7-9. Simulated annual air temperatures in Myitkyina dwelling (living room) - annual values in box charts.

The results also revealed that the Model A would need more cooling demand to keep the comfort hours below AT 25°C due to its highly airtight, super-insulated thermal envelope. On the other hand, the Model B would need more cooling demand to avoid the overheating frequency above AT 36°C. It was found that Model A had a higher percentage of the annual hour for the indoor AT above 25°C regardless of scenario differences; however, Model B had higher percentages of the annual hour for the indoor AT above 36°C regardless of scenario differences. The results of the comparison of indoor air temperature 25°C and 36°C revealed that the building envelope with Passivhaus scenario would perform better in reducing peak interior temperatures but would keep indoor AT above 25°C.

Wet-bulb temperatures: Figure 7-10 presents the comparison of WBT in different scenarios. The WBT below 25°C decreased in 2018 and future climate scenario regardless of model and ventilation scenario differences.

For the historical weather year 2018, the WBT values above 30°C were found to be 5.05%, 6.86%, 2.42%, and 2.88% of the annual hours for Model A with ventilation V1 scenarios Model B, ventilation scenario V1, Model A with ventilation, V2 scenario, and Model B with ventilation scenario V2, respectively. For the future climate scenario, the WBT values above 30°C were found to be 1.59%, 7.63%, 0.66%, and 0.74% of the annual hour for Model A with ventilation V1 scenario, Model B with ventilation scenario V1, Model A with ventilation V2 scenario, and Model B with ventilation V2 scenario, respectively. The results showed that Model B maintained a high WBT for a higher percentage of the annual hour than Model A, and the ventilation scenario V2 performed better than ventilation scenario V1 in the Myitkyina climate.

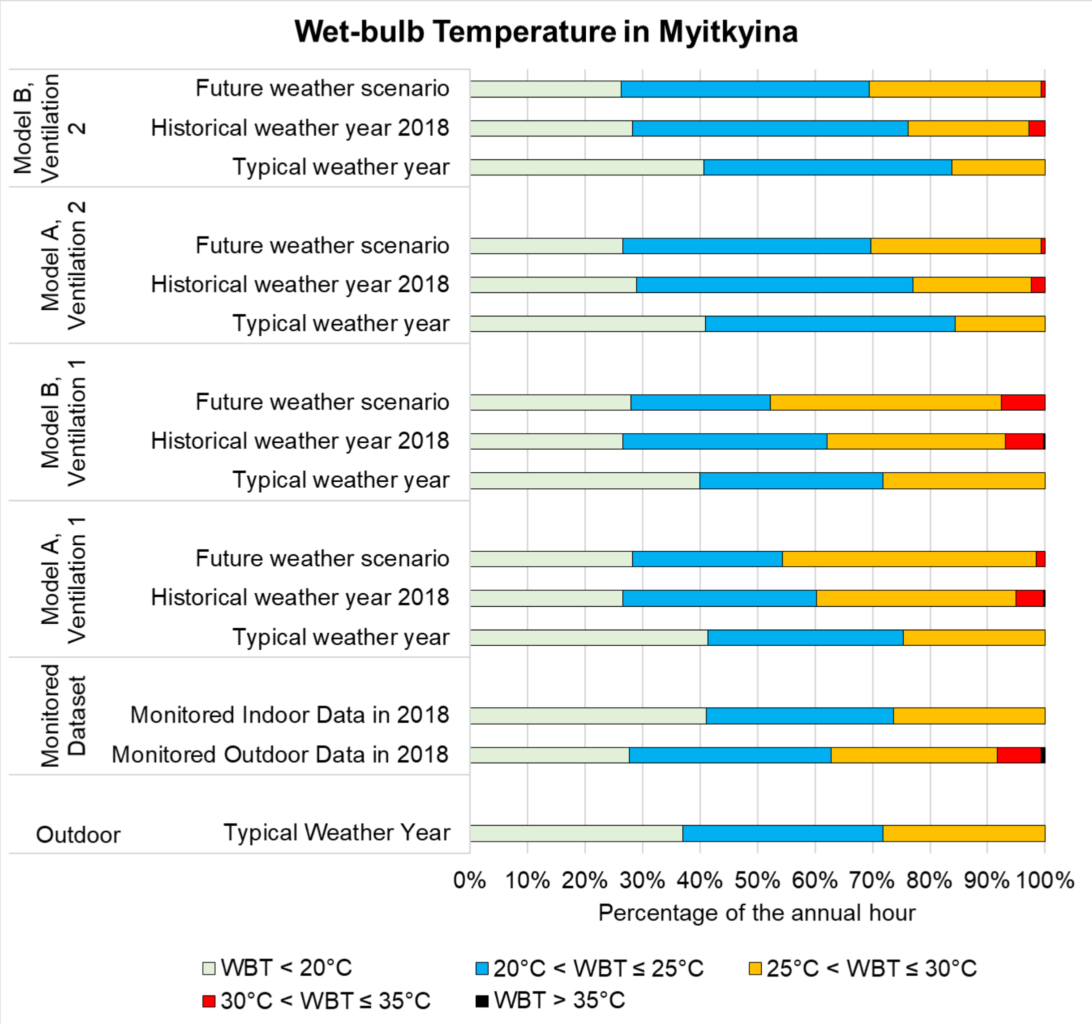

Figure 7-10. Annual wet-bulb temperature in Myitkyina in different scenarios

Heat index temperatures: Figure 7-11 presents the comparison of HT in different scenarios. The HT below 32°C decreased in 2019 and future climate scenarios regardless of model and ventilation scenario differences. In the Model A, ventilation scenarios V1, the HT, above 41°C were found to give 0.74%, 12.74% , and 12.87 of the annual hours for typical weather year, historical weather year 2018, and future climate scenario, respectively. In the Model B with ventilation scenario V1, the HT values above 41°C were found to be 1.36%, 13.55% and 15.46% of the annual hours for typical weather year, the historical weather year 2018, and future climate scenario, respectively. The percentage of the annual hour above HT 41°C was reduced in ventilation scenario-2 due to the daytime cooling from the mechanical ventilation. Like the MDY dwelling, the results showed that Model A maintained a high HT and

WBT for a higher percentage of the annual hour than Model B in the Myitkyina dwelling.

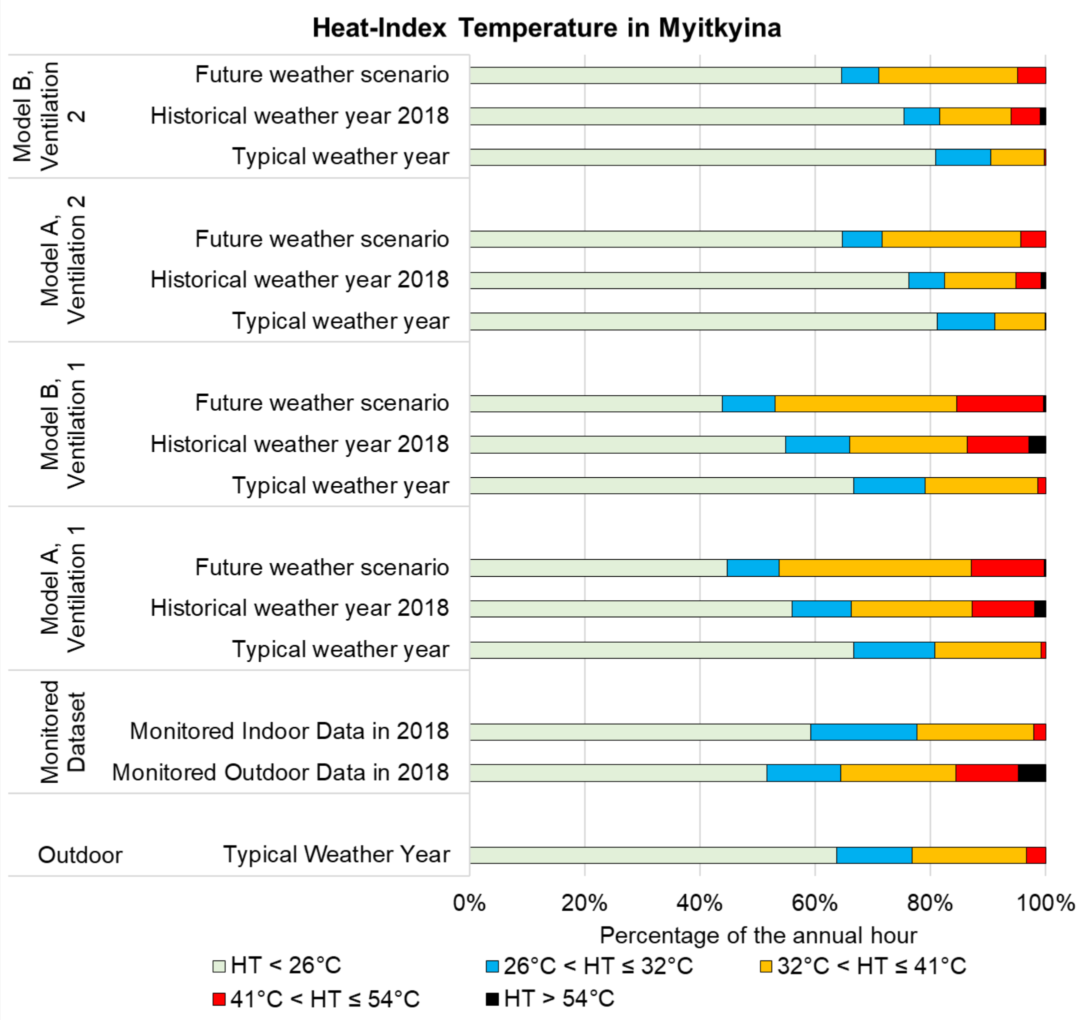

Figure 7-11. Annual heat index temperature in Myitkyina in different scenarios

7.3 Discussion

This section presents the findings of the two simulation sets and their comparison to the empirical datasets and the outdoor weather. It then discusses the performance of Passivhaus and partially Passivhaus scenarios in the future climate scenarios, the limitations of the study and suggested future work.

Impact of form factor: The MDY dwelling has a form factor of approximately 4.42, and the MKN dwelling has a form factor of approximately 3.92, which are higher than the favourable form factor of 3 for economic reasons. Further study is necessary for the cost analysis and the impacts of form factor for energy-related studies.

Impacts of U-value: This study hypothesised that a slightly higher U-value for walls and floors could be more effective for the local climate than the very low U-value suggested by the Passivhaus standard. Model B represented a scenario with a slightly higher U-value for walls and floors. The hypothesis was true as the partially Passivhaus scenario can keep a slightly lower air temperature between AT 25°C and 36°C range in the typical and historical weather years. However, the effect was increased when observed indoors with AT above 36°C; at that time, the Passivhaus model performed better than the partially Passivhaus model. In the future climate scenario, a prediction can be made that the Passivhaus scenario would perform better than the partially Passivhaus scenario.

As the indoor air temperatures were decreased in the ventilation scenario V2 in both Models A and B, as shown in Figure 7-4 and Figure 7-9, the results revealed the adaptability of the Passivhaus concept in the studied climate to improve the building thermal performance for future climate change conditions. On the other hand, a better result was found in the monitored data set, which was based on a common construction type in Myanmar, i.e., not a Passivhaus thermal envelope. However, it is impossible to state that real-world condition would perform better than the experimental model in future climate scenarios, as shown in Figure 7-3 and Figure 7-8. Detailed records on occupant behaviour, window opening times, and the effect of internal heat gain are indispensable factors for the effective realisation of modelled predictions in reality.

Impacts of thermal mass: In Chapters 4 and 5, the effect of thermal mass was considered and investigated, showing that a higher thermal mass could lower the overheating percentage. On the other hand, the relationship between the impacts of thermal mass (which could exacerbate heat retention) and the high-temperature events are not known. As the effect of a high thermal mass could exacerbate the annual mean temperatures, this present study was structured to investigate the PassivHaus suggestion of U-values with lightweight construction type; therefore, the decrement delay advantages of thermal mass effect did not contribute to the results.

Impacts of temperature and humidity thresholds: As the Passivhaus' suggestion of the overheating threshold is not directly applicable for a naturally ventilated condition in the tropical climate, the present study used the wet-bulb and heat index temperatures to check the heat stress (including the humidity factor) in the results of simulated models. It was found that the Passivhaus scenario (Model A) maintained a higher percentage of the annual hour for high heat index and wet-bulb temperatures than the partially Passivhaus scenario (Model B) in both dwellings. That revealed the effects of high humidity in high air temperature. As the prescribed scenarios were not designed based on the Passivhaus' suggestion of mechanical ventilation and heat recovery, including the dehumidification effect, it was impossible to state that the tested partially Passivhaus scenario would perform better in the real world Passivhaus building in the studied climate. Further studies are necessary for the temperature and humidity thresholds for the tropical Passivhaus building, both for the building thermal performance design parameters and for the local residence adaptability.

Impacts of ventilation: The simulation models were considered in the proposed three ventilation scenarios. Ventilation scenario V1 represented adaptive comfort models rather than the PHPP's heat-balanced model format. Ventilation scenario V2 applied mechanical ventilation for daytime cooling, and scenario V3 was the heat-balanced condition. Understandably, the natural ventilation alone could not provide adequate building thermal comfort. Nevertheless, further study is necessary to investigate the window opening behaviour of Myanmar dwellings in terms of respective climatic elements and cultural factors. Further study is also necessary to investigate differences between impacts of three thermal comfort modes: the heat-balance condition with active ventilation design, the adaptive comfort condition with natural ventilation design, and the mixed-mode ventilation.

Indoor air quality: The present figures of CO_2 concentration in the monitored data sets showed a good indoor air quality due to the use of natural ventilation (note that the high-level windows at the backside of the wall allow cross-ventilation). A mechanically ventilated Passivhaus building offers an excelling indoor air quality using a F7 filter for the intake air and a G4 filter for the extract air (Feist et al., 2019). If a building is considered a Passivhaus building envelope with natural ventilation, further studies will be required to address indoor air quality.

Impacts of airtightness and construction: 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, p126). The vernacular construction practices in Myanmar, as shown in the vernacular house study (Chapters 1 and 3), the Passivhaus' certification of airtightness requirement is indeed a challenge to control the air infiltration and exfiltration, to say nothing of constraining the thermal bridge factor (psi value ψ) to be less than 0.01 W/mK. The performance gap does not occur with the Passivhaus standards following the Passivhaus guide through PHPP, educating the contractors and tradespeople, using certified Passivhaus components. Nevertheless, all these factors are still a challenge, requiring careful attention and details design in Myanmar. Challenges in Passivhaus construction was discussed in Section 2.2.

7.4 Conclusion

This chapter investigated the application of the Passivhaus fabric-first approach in Myanmar whether the Passivhaus concept is adaptable in tropical climates considering methodological differences between the fabric-first approach building envelope and tropical vernacular construction practices. It was hypothesised that a slightly higher U-value for walls and floors could be more effective for the local climate than the very low U-value suggested by the Passivhaus standard. The simulation experiments were performed and validated with the empirical data sets to answer the research questions of this chapter, which were also RQ11 and RQ12 of the research questions of this thesis.

Answer for research question 1: The fabric-first building envelope approach might perform well against the high temperatures outside, but a shorter interquartile range of the Passivhaus and partially Passivhaus scenario (Figure 7-4 and Figure 7-9) could entail a more modest impact than vernacular lightweight, non-insulated buildings, and the effect could be more profound if a high thermal mass with decrement delay advantages further contributes in the insulated building envelope.

Answer for research question 2: Several barriers such as the specific thermal threshold for the tropical climate, the challenges in airtight construction, the lack of economic analysis were discussed. Those barriers together, with the lack of skilled construction workers, Passivhaus technicians and tradespeople, could affect both the comfort and quality assurance standard of Passivhaus construction, making it difficult to obtain certification or produce the commensurate building quality. As the current Myanmar banking systems do not provide loans for construction, that could be a financial barrier to the adoption and deployment of Passivhaus construction. Besides the economic concerns (knowledge adapted from the cold climate context), it was also found that the monitored dwellings presented better results than the Passivhaus scenario (Model A) with ventilation scenario V1 (Figure 7-3 and Figure 7-8).

Despite the limitations discussed and presented for the predefined conditions in the simulation models, the present study is particularly important in improving the building thermal performance design in Myanmar housing in the face of rapid climate change. The findings of this study could highlight the adaptability and potential of the Passivhaus concept in the tropical climate context. Nevertheless, further investigation is necessary for a better understanding of the ‘real-world’ behaviour of the Passivhaus concept in the tropical climate and the Myanmar context to establish the robustness of the approach.

Overall, this chapter contributes to establishing tailored information to unify the Myanmar building code and potential influence on future policy relating to building thermal performance design in Myanmar that will support mainstream climate change into the Myanmar housing policy development.

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History had given us

the opportunity to give of

our best for a cause

in which we believed.

History is always changing.

~ Aung San Suu Kyi

from Nobel speech in Oslo, 16 June 2012

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8. Conclusion and Future Works

The four objectives of building thermal performance in Myanmar housing in a changing climate condition was investigated in this thesis to provide significant improvement to develop a standard for building thermal performance design in Myanmar housing. That underpins the research questions reiterated and summarily answered below, with a summary of the salient findings of the individual case studies. The four objectives were to review and investigate -

I. Lessons learnt from Myanmar vernacular architecture.
II. The impacts of climate change and overheating risks in Myanmar housing.
III. The impacts of the Passivhaus' fabric-first approach on the Myanmar contexts.
IV. Barriers, challenges, and limitations of adopting the Passivhaus' fabric-first approach in Myanmar.

8.1 The original research questions

The “case study research method with multiple cases” was adopted in this thesis whereby three case studies - (i) vernacular case studies, (ii) field case studies, and (iii) fabric-first variable case studies - set out to provide findings for research objectives and answer research questions. The findings of the case studies are presented in this chapter, answers the research questions, and discusses future challenges and closing remarks of the thesis.

8.1.1 Vernacular case studies

As Oliver (1986) asserted, the technological merits of vernacular traditions do need to be studied and understood, and the extent of vernacular knowhow does demand to be examined and recognised. This study was attempted to fill the research gap of Myanmar vernacular, and different vernacular practices of Myanmar housing and traditional buildings in the way they provide thermal comfort were investigated. The vernacular case studies presented in this thesis contribute to achieving the first objective of the lessons learnt from Myanmar vernacular architecture, which posed the following research questions:

1. How do the vernacular practices in Myanmar housing provide thermal comfort, and does the building thermal performance of Myanmar vernacular housing cope with climate change?
2. To what extent can the resilience of vernacular passive design techniques used in Myanmar housing improve the indoor thermal environment for future climate scenarios?

Approach to explore the research questions: The passive building design techniques used in Myanmar vernacular housing for thermal comfort based on the results of a field visit to the National Races Village was reviewed in Chapter 1, which showcases eight Myanmar vernacular houses, which are replicas of significant symbolic structures characteristic of the major ethnicities residing in the country. Furthermore, a thorough review of "Pyatthat" traditional tiered (multistage) roof design is presented. Although buildings with multistage roofs are not popular in Myanmar housing, the knowledge of passive design techniques in Myanmar vernacular architecture is important to appreciate, as a new insight can be developed for further studies. Both reviews provide information for further simulation studies in Chapter 3. Changes in the use of building envelope materials were a focus of both studies by comparing vernacular materials (lightweight timber walls with thatch roofs) and their customs (brick walls, metal roof and concrete floors). The simulation case studies contributed to the knowledge of the ongoing resilience of the vernacular architecture and how the use of vernacular materials, layouts, and building forms can provide thermal comfort in Myanmar housing while identifying challenges in relation to yearly weather and predicted future climate scenarios.

Answers to the research questions: The review presented in Chapter 1 answered the research question RQ1. In light of this overview of traditional houses, a combination of various building components for passive design techniques (i.e., lightweight building envelop, roof insulation and roof ventilation) is ideally suited to maintain thermal comfort for the related tropical contexts. However, while some passive cooling design techniques have demonstrable utility, they have been lost in modern practices. For instance, the use of the raised floor allows the house to be ventilated by natural convection through cracks in the raised floor and offsets radiated heat gain from the hot-dry ground, in addition to protecting against flood and preventing moisture penetration from the wet ground.

Notably, the simulation experiments of the vernacular houses showed that the efficacy of traditional passive design techniques would not be sufficient to achieve thermal comfort in the predicted future climate scenario, as the resilience of natural ventilation techniques and other passive design features in Myanmar housing is decreasing due to the impacts of increased outdoor temperatures. The results of the multistage roof study showed that Myanmar’s traditional buildings with multistage roofs offer an opportunity to improve indoor comfort in tropical weather because of their adaptability for roof ventilation through gable vents, and the use of an abstract roof curve to divide the number of tiers and reduce roof internal air volume. The variable that impacted the most on the results was roof ventilation mode, with the best results being 3.5% of the annual hours better than the worst. The multistage roof was found to help reduce heat gains from solar radiation. However, it was also found that the building envelope materials and roof ventilation play a role to alter the thermal performance of the studied buildings.

Although the stack effect of roof ventilation was not noticeably observed in the Myanmar vernacular house, the CFD simulation results for a building with a three-stage hipped roof showed that its indoor air temperatures were lower than a building with a single gable roof; however, along the vertical planes from 2.5m onward, the indoor air temperature increased in the building with a three-stage hipped roof. The vertical planes of airflow profiles were generated in the CFD program from the plane which was parallel to the inlet wind direction. The radiant temperature differences along the vertical planes of the building with a three-stage hipped roof were not observable; however, the air temperature differences between the floor level to 9m height were more than 1.5°C. Therefore, if the Passivhaus approach with natural ventilation is considered in the building with multistage roofs, the vertical temperature difference needs to be investigated. Note that the IESVE's ApacheSim only provides the surface temperature but does not provide the vertical air temperature difference.

The findings of the simulation study presented in Chapter 3 also answered the research question RQ2. Natural ventilation and roof shading in Myanmar vernacular architecture might have been an optimal thermal comfort performance in the past; however, the increasing outdoor temperatures and changes in rainfall caused by global warming and climate change are threatening the thermal performance of Myanmar housing. Both studies presented in Chapter 3 revealed that there is a need to improve the thermal performance of Myanmar vernacular houses and traditional buildings. It was concluded from these investigations that the thermal performance of vernacular buildings in Myanmar could be enhanced by building envelope materials and roof shading, together with the use of natural ventilation.

8.1.2 Field case studies

This thesis was developed based on the concerns of the climate change impacts on Myanmar housing, particularly for the thermal performance of detached house type. Three important research gaps in Myanmar housing were introduced in the 'Introduction' section of this thesis. In order to fill these research gaps, this thesis was structured to contribute empirical and quantitative assessment of the thermal performance of Myanmar housing, based on the review of Myanmar vernacular architecture. The field case studies presented in this thesis contribute to the second objective of the investigation of the impacts of climate change and overheating risks in Myanmar housing, which posed the following research questions:

3. What are the differences between the typical weather year and recent weather year, and how those changes in climates impact the thermal performance of Myanmar housing?
4. How do the vernacular and modern dwellings in Myanmar thermally perform in the present weather year compared to a typical weather year?

5. How does the building thermal performance vary in terms of the building envelope design, i.e., in vernacular and modern buildings?
6. How do different local climates affect the building thermal performance design in future climate scenarios?

Approach to explore the research questions: The fieldwork investigations of the indoor thermal performance of vernacular and modern dwellings in Myanmar were presented in Chapters 4 and 5. The case studies with fieldwork filled the knowledge gap by presenting the analysis of an empirical data set collected in typical dwellings over one year, including microclimate data collected in rural and urban settings and the analysis of typical dwellings modelled in dynamic simulation software and validated by the empirical data. The case study of vernacular dwelling highlighted the modern customs in the use of building materials and compared two cases: a base case of vernacular timber wall envelope and a tested case of brick wall envelope. The case study of modern dwelling highlighted the modern customs in the use of ventilation strategy even the building envelope materials were changed to thick brick walls. Using empirical data sets and simulations, the building thermal performance studies for two dwellings were combined to produce an understanding of how climate affects the performance of the observed buildings in two of Myanmar's climates.

Answers to the research questions: The results of monitored data sets presented in Chapters 4 and 5 answered the research question RQ3. The empirical data sets of Myitkyina found that the occurrence of hours with outdoor dry bulb temperature above 30°C increased by 1.8 times, and warmer hours above 36°C increased eight times in 2018 compared to a baseline typical weather year; furthermore, the hot and cold seasons in the year 2018 were drier than in the typical weather year. The empirical data sets of Mandalay found that the occurrence of hours with the indoor air temperature above 30°C were double those of the baseline year in 2018, and there were changes of monsoon onset and withdrawal time in 2018 compared to a typical weather year.

The validation between monitored data sets and simulation results presented in Chapters 4 and 5 answered the research question RQ4. As the vernacular Myitkyina dwelling showed a close relation to the weather outdoors, changes in outdoor dry bulb temperature and relative humidity could pose risks to the occupants in all free-running Myanmar dwellings due to their dependence on the heat-humidity threshold, according to the outdoor weather. Despite the use of a thick brick wall for thermal mass, the modern Mandalay dwelling also showed that the indoor thermal environment of the monitored dwelling had a close relation to the outdoor weather, which could be due to its use of natural ventilation. As the weather outdoors has changed in both locations, its impacts of high daytime temperatures and increased night-time temperatures had a significant impact on both dwellings. As a result, in both dwellings, the comfort hours were decreased, and the annual indoor mean temperatures were increased. Despite changes in outdoor weather, the empirical datasets showed that both dwellings maintained lower indoor temperatures than their outdoor temperatures.

The results of the analysis, which were generated for the indoor thermal performance of the monitored dwellings with different thermal envelope scenarios, answered the research question RQ5. There were three main differences between the two empirical data sets. The first one is their location setting: the Myitkyina dwelling represents Koppen climate Cwa, and the Mandalay dwelling represents Koppen climate Aw. The second one is their construction type: the Myitkyina dwelling represents a vernacular construction type, and the Mandalay dwelling represents a modern construction type. Both dwellings were monitored at different times. Therefore, it is impossible to compare the two associated data sets. Despite those differences, it can be seen that the vernacular dwelling was more closely influenced by its outdoor weather, whilst the modern dwelling maintained its indoor mean temperature against outdoor diurnal temperature swings. That resulted in their differences in indoor wet-bulb temperatures and heat index temperature, in which the relative humidity is factored in with air temperature.

The empirical data sets revealed that the vernacular dwelling in the Koppen climate Cwa maintained wet-bulb temperature below 30°C when the outdoor weather had 8.5% of the annual hours above wet-bulb temperature 30°C. The web-bulb temperatures did not reach above 30°C in the Koppen climate Aw; therefore, the modern dwelling maintained 48.5% of the annual hour below wet-bulb temperature 30°C when its outdoor weather had 51% of the annual hour. This comparison showed that the vernacular dwelling could maintain a lower wet-bulb temperature than the modern dwelling by means of (1) its use of natural ventilation through the highly infiltrated building envelope and (2) the impacts of outdoor weather (as the Koppen climate Cwa has a larger diurnal temperature swing than the Koppen climate Aw).

On the other hand, the summer temperatures of the Koppen climate Cwa were higher than the climate Aw; therefore, the vernacular dwelling in the Koppen climate Cwa was more affected by high summer temperatures. As vernacular and modern dwellings showed different performance for the peak and mean temperatures, it is impossible to draw a clear line for their advantages and disadvantages in the present climate. Both dwellings performed better in a typical weather year compared to the recent weather years 2018 and 2019. Nevertheless, both dwellings did not give an adequate performance to meet comfort requirements throughout a year.

The simulation results for future climate scenarios presented in Chapters 4 and 5 answered the research question RQ6. From the findings of the empirical data sets, it can be concluded that the buildings in the climate Cwa have a higher risk of peak summer temperatures than the climate Aw, despite a large diurnal temperature swing found in the climate Cwa. In 2018, 0.7% of the annual hour was above the wet-bulb temperature 35°C, which is beyond the upper physiological limit (Pal and Eltahir, 2016, Raymond et al., 2020). That also alerted the emergence of heat and humidity is too severe for human tolerance in Myanmar; unquestionably, a more in-depth investigation is required for the scope of building thermal comfort in Myanmar. In the future, both climates might be affected by changes in the monsoon season; furthermore, a high heat index and wet-bulb temperature might be a challenge for buildings in both climates. Considering all those effects together, the evidence of the empirical data sets revealed that there is a serious challenge posed by humid heat in the recent climates of Myanmar and Myanmar housing that is more intense than a typical weather year, with increasingly severe outcomes.

Naturally ventilated buildings in the tropical climate always need to respond to humid heat for thermal comfort; however, the resilience of passive design features used in tropical vernacular architecture has decreased due to the fundamental increase in wet-bulb temperatures and the risk of heat stress has consequently increased. These adverse effects of climate change on buildings, both from sudden extreme weather events and slowly changing climatic conditions, have profound impacts on the health, comfort, and quality of life of occupiers. This could affect building thermal performance design for Myanmar housing in future climate scenarios. The findings of the field case studies contributed valuable insights, such as an understanding of the vulnerability of homes to overheating in Myanmar, particularly from the impact of climatic elements on thermal comfort, the impacts of changes in monsoon onset and withdrawal time, warmer night temperatures, the urban heat island effect on the indoor thermal environment, and the impacts of different building envelope materials.

8.1.3 Fabric-first variable case studies

The Passivhaus' fabric-first approach was introduced in this thesis with an aim to search possible approaches in improving the building thermal performance of Myanmar housing for the present and future climate scenarios. If the Passivhaus' fabric-first approach is applied in the tropical climate context, which by definition differs from cold climate characteristics, whether the concept is adaptable in the Myanmar context is a question concerning the tropical climate elements and building thermal envelope design, particularly if a house uses an adaptive thermal comfort model. Therefore, a hypothesis below was proposed in this thesis.

> **"There is potential and possibilities to improve the thermal envelopes of Myanmar housing in the tropical climates by the use of optimum variables from the fabric-first approach originated from the PassivHaus standard".**

In order to test the hypothesis, a series of case studies were presented in Chapters 6 and 7. The fabric-first variable case studies using a simplified model contributes to the third objective of the investigation of the impacts of the Passivhaus' fabric-first approach on the Myanmar contexts, exploring shading and roof materials. The fabric-first variable case studies using studied dwellings contribute to the fourth objectives of the review of barriers, challenges, and limitations of adopting the Passivhaus' fabric-first approach in Myanmar, which posed the following two groups of research questions.

Fabric-first variable case studies in a simplified model

7. Which Passivhaus parameters are more sensitive in tropical climates compared to cold climates?
8. How do the synergistic effects between shading and the Passivhaus thermal building envelope influence the tropical Passivhaus building design?
9. How do the synergistic effects between the cool roof and the Passivhaus thermal building envelope influence the tropical Passivhaus building design?

Approach to explore the research questions: The literature review presented in Chapter 2 formed the basis for the development of two hypotheses for tropical Passivhaus buildings in the Myanmar climate contexts and informed that Passivhaus building envelope material properties with shading could be of relevance to either cold or tropical climate contexts. For the shading study, it was hypothesised that a slightly higher U-value for wall and floor could be more effective in Myanmar climates than the very low U-value suggested by the Passivhaus standard; the hypothesis can be sufficient in the tropics to achieve Passivhaus targets if the synergistic effects between shading and building envelope design were considered. For the roof material, it was hypothesised that if the roof has a cool roof effect with low solar absorptivity and high thermal emissivity, “the higher the U-value, the better” could overwrite “the lower the U-value, the better,” which is a characteristic of reflective insulation.

Answers to the research questions: The simulation results of the shading study presented in Chapter 6 Section 6.1 answered the research questions RQ7 and RQ8. In the shading study, firstly, the review of thermal comfort thresholds was linked to this study 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 when we investigated the impacts of other parameters that are not included in the Passivhaus calculation. Finally, a simulation study was focused on limited thermal envelope parameters, exploring only three thermal mass and two types of floor material, and six shading scenarios, to test 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. Particular focus was given to discuss the impacts of thermal mass, shading, U-values, and ventilation on comfort levels.

The simulation results revealed that 3.6% of the annual overheating time could be reduced by adding 1m roof extension, window overhang, and internal shading to a Passivhaus building envelope with heavyweight construction, but the same measures are effective for only 0.62% of the annual hour for non-Passivhaus lightweight buildings. Passivhaus building envelopes with external shading can substantially improve thermal comfort for future climate scenarios in Myanmar. The results also revealed that the Passivhaus building envelope performs better than the typical lightweight, not-insulated building envelope in the Myanmar climate. Unlike the Passivhaus buildings for the cold climates, the thermal capacity in walls and U-values in walls and floors are more sensitive in Passivhaus building for tropical climates because the drawback of super-insulation in a heavy-weight wall is its generally high degree of annual and daily mean temperatures; put simply, it is effective in mitigating against acutely high temperatures, but at the expense of elevated mean temperatures during normative conditions.

The findings of the shading 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 technology solutions through building fabric and potential hybrid ventilation. It was found that the positive effects of roof eave shadings and window shadings are more sensitive when they are associated with the Passivhaus thermal envelope.

The simulation results of the roof material study presented in Chapter 6 Section 6.2 answered the research questions RQ7 and RQ9. In the roof materials study, which was conducted for reflective shading effect on the highly insulated building envelope, it was found that the resistive insulation approach of “the lower the u-value, the better to slow down the flow of heat into the building” was more applicable for the roof in all Myanmar climates if the exterior finish had high solar absorption. In this case, the conductivity of the material was crucial, related to increasing the size and the building weight, which raised challenges for earthquake-resistant structural design. If the roof has a cool roof effect with low solar absorptivity and high thermal emissivity, “the higher the u-value, the better” could overwrite “the lower the u-value, the better,” which is a characteristic of reflective insulation. In this case, the surface colouration of roofs and exterior walls is crucial, entailing extra maintenance for the use of high albedo.

The findings of the roof material study highlighted that it is important to take the impacts of capacitive insulation into account when the resistive insulation and reflective insulation are compared. The capacitive insulation is also a challenge for earthquake-resistant structural design. Additionally, the impact of the position of insulation must be considered, such as cool-walls and heat-emitting-walls, which were not investigated in this study. Finally, it can be suggested that the possibilities to improve the efficacy of natural ventilation should be considered with close attention to effectiveness in particular studied climates. It is worth considering the importance of different insulation effect and ventilation variables for improving thermal environments for all Myanmar climates. Careful design with fenestration and ventilation variables can further improve the indoor thermal environment. In essence, the findings of these simulation studies contribute to research on climate-specific solutions, depending on the boundary conditions in individual contexts. Note that the hypotheses tested in these studies were supported the main hypothesis discussed in the 'Introduction' section.

Fabric-first variable case studies in studied dwellings

10. How does the Passivhaus building envelope differ compared to the vernacular construction in Myanmar?
11. How does the Passivhaus' fabric-first building envelope approach perform differently according to the climate differences in Myanmar?
12. What are the challenges of adopting the Passivhaus' fabric-first approach in Myanmar in terms of its original context, climate, and methodology differences?

Approach to explore the research questions: Whether the Passivhaus' fabric-first approach is adaptable in the tropical climates in terms of their methodology difference between the Passivhaus' fabric-first approach building envelope and tropical vernacular construction practices, it is essential to compare the predicted performance of tropical Passivhaus and actual performance local dwellings. Chapter 7 presents an extension of the field studies, where the building envelopes of the dwellings were switched to Passivhaus parameters using simulation experiments. The simulation experiments performed using Passivhaus parameters in the Myanmar context, validated with the empirical data sets from Chapters 4 and 5.

Answers to the research questions: The differences between Passivhaus and vernacular (non-Passivhaus) building envelope configurations were found both in annual temperature ranges and peak air temperatures; the initial findings of the shading study presented in Section 6.1 answered the research question RQ10. In the study presented in Chapter 7, it was also found that the fabric-first building envelope approach gave effective performance against high outdoor temperatures, regardless of slightly different climate contexts (for Koppen climate Aw and Cwa). A more modest impact was achieved using a shorter interquartile range of Passivhaus (Model A) and partially Passivhaus scenario (Model B, increased U-value in wall and floor) compared to vernacular lightweight, non-insulated buildings. It was also found that the

Passivhaus scenario maintained a higher percentage of the annual hour for high heat index and wet-bulb temperatures than the partially Passivhaus scenario in both dwellings if there is no mechanical ventilation. That revealed the effects of high humidity in high air temperature. This effect could be more profound if a high thermal mass with decrement delay advantages further contributed to the insulated building envelope.

The comparison between the Myitkyina dwelling and Mandalay dwelling answered the research question RQ11. Applying daytime mechanical cooling to the studied dwellings gave a shorter interquartile range in the climate Cwa, which means a Passivhaus building might maintain more consistent temperatures in buildings in the climate Cwa compared to the buildings in the climate Aw. Although the energy-efficient ventilation system was not integrated into this thesis, understandably, applying the Passivhaus building envelope with ventilation scenario V2 and V3 would bring adequate building thermal comfort with low energy consumption.

In order to answer the research question RQ12, several barriers, such as the specific thermal threshold for the tropical climate, the challenges in airtight construction, cost and economic analysis, are necessary to consider in adopting the Passivhaus' fabric-first approach in Myanmar. The current housing practices (both in vernacular strategies and building design evolution with modern customs, as presented in Chapter 1) showed that barriers in adopting the Passivhaus standard and also linked to both social, economic and technological constraints; that would be the challenges of an emerging market in promoting the Passivhaus standard in Myanmar. Those barriers, together with the lack of skilful Passivhaus technicians, could affect both the comfort and quality assurance standard of the Passivhaus to meet the certification standards. Despite the limitations discussed and presented for the prescribed conditions in the simulation models, the findings of the simulation experiments contributed knowledge and agree with the main hypothesis presented in the ‘Introduction’ section that there is potential to adopt the Passivhaus fabric-first approach in the tropical climate context to improve the building thermal performance and cope with climate change impacts on tropical buildings.

8.2 Limitations

The case studies provided in this thesis were generated from the empirical data sets and simulation experiments for two dwelling types of Myanmar from two climates. The simulation results obtained in this thesis were in part limited due to reliance on the quality of weather files. The lack of existing literature review of the building thermal performance of Myanmar housing, qualitative assessment for thermal thresholds in the Myanmar context, and PHPP analysis, as well as the small scale of monitoring work, all comprise limitations of this thesis. However, whilst the monitored dwellings may not be representative of all dwellings in Myanmar, they do represent passive design strategies, the fundamental construction materials used, and the building envelope performance for the studied climate. The validation between the empirical data sets and simulation data sets enhanced the quality of the findings. The studies presented in this thesis could be more comprehensive if a real-world building is tested using the optimum variables from the fabric-first approach originated from the Passivhaus standard, from which barriers and challenges of Passivhaus' construction practices can be learned. Despite the earthquake design requirements for a detached house [Figure 1-23], there were limited building regulation and practice discussed for construction practice in Myanmar. There were conflicts between Passivhaus' airtight construction requirements and highly infiltrated Myanmar housing practice. Retrofitting is a solution to improve the building thermal performance of the existing stock, for which strategies are required to develop in terms of its retrofit-ability for technical and spatial requirements; that should be considered in future research. These fabric-first variable case studies were particularly relevant given the fact of the vulnerability of homes to overheating in Myanmar; the implications of the findings would be more effective if good practices and guidance of Passivhaus construction are developed for the Myanmar context. Therefore, a number of recommendations and future works are provided which would contribute to the strengthening of the findings of the thesis. Overall, despite the time parameters surrounding this project and its limitations, the research presented in this thesis contributes in-depth knowledge of vernacular design features for passive design and pioneering new knowledge to enhance building thermal performance design for tropical housing in a changing climate.

8.3 Future works

In the age of climate change crisis, the language of buildings is bilingual, encompassing the voice from vernacular and the increasingly loud voice calling for changes to high thermal performance buildings, with low energy use like Passivhaus. Both need to be paid much attention to design buildings with sophisticated technical knowledge that can meet current and future user needs. Furthermore, it is necessary to consider the cultural and convenience factors and perceptions concerning ‘modern’ approaches, as well as environmental performance, which influence the decision to adopt or abandon particular vernacular approaches and features (Foruzanmehr and Vellinga, 2011, IPCC, 2014a, p693). If the limitations discussed and the applicability and feasibility of adopting the Passivhaus in the tropical climate context are considered, the following future research directions are identified to extend the findings of this study.

- The studies presented in this thesis focused on improving the indoor thermal performance of a changing climate condition in the future. In a broader sense, the interactions between climate change mitigation and adaptation strategies in the built environment and flourishing human capabilities depend on all large-scale environmental protection from the regional to the urban to the building scale, including outdoor environmental quality, indoor environmental quality, outdoor thermal adequacy and indoor thermal adequacy (Klinsky and Mavrogianni, 2020). As the indoor thermal environment of the studied dwelling showed a close relationship to its outdoor, it is vital to recognise the inextricable link between the outdoor and the indoor. Further studies are necessary, analysing large monitoring data sets with more rigour for validation of building thermal performance for various typologies and different building types, considering their directly influenced from the outdoor, to create a more robust evidence base for use.

- Vernacular architecture in Myanmar has been influenced by adaptation to the weather outdoor. The overheating and climate justice study for multifamily housing showed that showed adaptation measures require more than technical interventions (Schünemann et al., 2020). There is a need for a systematic and comprehensive review of building thermal performance design and quality assessment for occupant behaviour and thermal comfort, both for short-term and long-term changing climate conditions in the Myanmar contexts.
- The mitigative potential of the built environment and its microclimates has relied on its climate risk exposures and vulnerabilities (as presented in Section 1.1.1). In Myanmar, the gap is the universal gap like other countries that are currently present at the policy level, where there is a lack of specific recognition of the impact of buildings on their urban environment and microclimate (Schiano-Phan et al., 2015). More accurate climate data is required regarding the rural and urban areas, including long-term climate change projections for different weather scenarios, the El Nino effect and the climate change risk. That would improve a detailed assessment in building thermal simulation studies both in dynamic simulation software and PHPP for Passivhaus.
- The context of the thesis was to investigate the building thermal performance through its envelope design quantitively; therefore, the thermal comfort parameters generated by occupants, which could be subjective to the context, were not investigated. Future studies are necessary to evaluate whether Myanmar occupants perceive thermal comfort in Passivhaus buildings. For instance, 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. As people's adaptability and the nature of building use are different between airtight Passivhaus building and highly infiltrated vernacular buildings,

occupant behaviour and behaviour change studies might review the thermal threshold for the internal environment and overheating algorithm in PHPP.

- All the simulation experiments presented in this thesis highlighted that natural ventilation alone is likely to be insufficient to keep the indoor building thermal comfort within acceptable limits; this also highlighted the need for the development of building thermal envelope performance using the Passivhaus' fabric-first approach, aiming to achieve comfortable indoor conditions with extremely low heating and cooling loads. The latter objective of Passivhaus low energy demand was not investigated in this thesis. Parametric and sensitivity analysis studies investigating the Passivhaus parameters and variables for the further thermal and energy performance of Myanmar housings, considering a broader range of building typologies in different locations of Myanmar.
- Only the effects of roof shading and window overhang on the tropical Passivhaus thermal envelope were investigated in this thesis. Further studies are required to investigate a variety of shading techniques, including the locations of balconies, canopies, loggias, porch and veranda.
- The CFD radiation model presented in Chapter 3 and the cool roof effect presented in Chapter 6 shows there are considerable effects of radiant temperature asymmetry and stack effect of ventilation in the pre-defined scenarios; that would affect determining the Passivhaus material properties. Future building thermal performance design for Myanmar need to consider as a whole building design with an integrated design approach, and attention is required in selecting building material.
- The field case studies presented in this thesis are only for the Koppen climate Aw and Cwa. According to Koppen climate shift in Myanmar from 1926 to 2100 (Figure 1.4, Chapter 1), the Koppen climate Am, tropical monsoon climate, would be more dominant in the future, and the most populated cities from the southern part of Myanmar, including the largest city Yangon, could be affected. Therefore, future works should focus on this aspect.

- Regarding the Passivhaus approach, the development of the airtight testing facility, construction skills and installing the MVHR system is crucial to enable the delivery of the Passivhaus building without a performance gap.
- The assumption of internal heat gain can never be accurate because the occupancy and technology associated with a building will vary. If the effects of internal heat gain for cooling load and thermal comfort are considered, further study is necessary to work to investigate the influence of Myanmar culture, demographic and family nature.
- The hybrid strategy is necessary for the Myanmar context to maintain adequate thermal comfort. In this respect, the successfulness of the Passivhaus approach in Myanmar contexts could measure in the ways the passive design approach building envelope can be switched to the mix-mode approach. Both theoretical investigation and real-world scenario research are thus necessary to investigate the impacts of mixed-mode and natural ventilation used in the tropical Passivhaus in terms of the risk of mould and condensation formation. For instance, if there is no MVHR running in the airtight building, poor ventilation will cause mould in the tropical climate. Note that the Passivhaus suggests reducing cooling and dehumidification demand through energy-efficient active cooling systems to minimise the energy demand; that also should be considered in hybrid strategies for future works.
- Visualising high building thermal performance design with low-energy architecture requires educating the designer (Hamza and Horne, 2007), including all the actors in the Myanmar AEC industry, for good practices and guidance of Passivhaus construction. The development of construction trade, Passivhaus training, and skilled labour is required, which should be affiliated with the PHI or other Passivhaus bodies for the educational links and transfer of Passivhaus knowledge in both design and construction worldwide, particularly in developing countries in greatest need of sustainable, energy-efficient construction techniques.

The list of future works in adopting the Passivhaus in the Myanmar context is virtually unlimited in terms of (i) academic research and real-world case studies, (ii) occupant behaviour and post-occupancy evaluation, (iii) procurement and supply chain, (iv) skills, training, and education, and (v) development as a standard in building regulation. Collaborative, multi-disciplinary, and (with regard to the work and recommendations listed above) overlapping efforts are necessary to comprehensively drive progress in sustainable, low-energy construction to meet user requirements in the coming years.

8.4 Closing remarks

The author developed this thesis based on the concerns of the climate change impacts on Myanmar, particularly for Myanmar housing. A distinct contribution to the knowledge of the subject and afford evidence of originality by the discovery of the new fact in this thesis was that, to our knowledge on the current literature, this thesis was the first study of building thermal performance design for Myanmar housing. This thesis filled the knowledge gap of assaying the fitness of vernacular and modern houses in Myanmar for future climate conditions and identified required improvements in building thermal performance and design.

Due to the shortage of empirical and quantitative assessments, one-year monitored data sets for two climates and extensive simulation case studies were presented in this thesis to study vernacular and modern houses in Myanmar with methodological rigour. The thesis hypothesised that there is potential to improve the tropical building thermal envelope in the studied climates using optimum variables from the PassivHaus standard fabric-first approach. This thesis highlighted a contrast between tropical vernacular practice in Myanmar and the Passivhaus requirements and also discussed barriers in adopting the Passivhaus standard in Myanmar in terms of cultural, social, economic and technological constraints.

Changes in the use of building envelope materials were a focus of all case studies by comparing vernacular materials (lightweight timber walls with thatch roofs) and their customs (brick walls, metal roof and concrete floors). Whilst the buildings with light-weight material would be more vulnerable to high outdoor temperatures in the future climate scenario than the buildings with Passivhaus building envelope even both have shading, adding insulation is adding the building own weight that could cause a plethora of often conflicting design requirements of earthquake resistance structure. External shading unquestionably has substantial impacts in all climate contexts, with numerous potential functional and aesthetic roles to play in addition to the traditional function of avoiding direct solar gain, including in the tropical climate of Myanmar. The shading and roof material case studies highlighted an alternative approach to meet Passivhaus' insulation requirements. The findings of this thesis provided original insights and a baseline understanding of the status quo that can be used to develop tailored information in establishing the Myanmar Building Code, with future research development to improve the quality of life with high building thermal performance design.

Our thermal comfort is determined by the way we balance heat gains and losses from the environment, pertaining to clothing insulation, shading, and air movement, by balancing the four elements: earth, water, fire, and air. Also, the fundamental laws of building physics do not change from one climate to the other climate or one culture to another. What we need to determine is the way in which we balance heat gains and losses from the given climate and local context. Indeed, comfort in living is far more in the brains than in the back (Richards, 1905, p62). What we can see from the Passivhaus' fundamental principle (Section 2.2) and suggested parameters are that the Passivhaus considers thermodynamic functions of human and buildings in the Great Four Elements (Table 2-1) in terms of the building physics to balance the heat gain and heat loss of the building using an active ventilation system.

Similarities and differences observed from vernacular architecture revealed how buildings are climatically coupled to the earth and the air in an objective manner in their building physicality, but subjective choices of building envelope type in responding to the climate elements and local contexts result in very different thermal outcomes. If a building is considered to be passive, there is always a need to investigate its responsiveness to an active outside climate.

When the climate changes, if the passive design strategies hardly meet the comfort requirement, the building thermal performance design might need to adjust and improve its resilience. The ‘resilience’ is about the understanding of change and approach two actions: adaptability and transformability (Garcia and Vale, 2017, p45). Future works of this thesis need to focus on this aspect of improving the thermal performance of Myanmar housing in a changing climate. In order to prepare for the climate change emergency to come, Myanmar needs a new story as well that embraces its diversity, celebrates its natural environment, and aspires to a new way of life (Myint-U, 2019, p258).

This is the first study in this research field investigating the indoor thermal performance of Myanmar housing based on the typical, recent, and future climate scenarios with an aim to present vernacular beauty and technical enhancement. Using multiple case studies method with empirical data sets and simulation experiments, the results of this research support the hypothesis, revealing that Passivhaus building envelope parameters and optimum variables can improve the tropical building thermal envelope of the studied climate for future climate change scenarios.

8.5 Postscript

The thesis was developed in 2016, just a year after the 2015 Myanmar general election, as a long period of isolation was officially ended. The focus of this thesis was to improve the thermal performance and resilience of Myanmar housing in a changing climate as the author strongly believe that the devastating impacts of climate change will not allow Myanmar to isolate politically. Using a case-study research method, empirical and quantitative assessments were presented. Whilst measurable data sets were demonstrated in this thesis using predicted future climate change scenarios, and it is also important to know that the living history of Myanmar will change any prediction of the future of the country.

Myanmar, a pariah state that had sealed itself off from the world until reopening in 2011, is resembling a bygone style of autocracy in 2021 (Fisher, 2021). On the 1st of February 2021, 50 million Myanmar people found that ten years of democratic progress in Myanmar are at risk after the 2021 Myanmar coup d'état. It was the day the doors of Myanmar opened to a very different future. Although it is difficult to see how things will play out over the coming weeks and months, as the Myanmar coup was meant to be a conservative reset, the coming months will probably see continuing strikes, heightened repression, violent resistance, and an agonising descent into needless poverty (Myint-U, 2021b). At the time of submitting this thesis, Myanmar is on the brink of state failure again, and the country remains ungovernable in 2021.

Selected international indices of the World Bank for 2010 (before the military rule ended) and 2020 showed that despite improvements in measures like corruption and democratic structures, the country remained in an extremely vulnerable situation (Buchholz, 2021). Just a few weeks after the military coup, on February 25, several local people reported that there was illegal logging of Ahlaungdaw Kathapha National Park in Sagaing Region, although the civilian government of Myanmar banned the export of raw logs of all species in 2014 (Forestlegality, 2016). Likewise, the World Bank announced a forecast that Myanmar's economy is expected to contract by 10% in 2021, despite a sharp reversal from the previous prediction of 5.9% growth in October 2020. This is the most devastating collapse since 1988 (Reuters, 2021). A briefing to the UN Security Council's 9 April 2021 clearly said that (i) the banking system is at a virtual standstill in Myanmar, (ii) supply chains are breaking down, (iii) the health system has collapsed, (iv) armed conflict is rising, and (iv) much of Myanmar's natural wealth is in the hands of unregulated actors (Horsey, 2021). Furthermore, the 2021 Myanmar coup d'état reveals that what has changed in Myanmar and what has not, and will also alter the country's future for all of its peoples.

Climate change is one of the greatest challenges collectively facing the world today. There are two components to respond to the challenge posed by climate change: addressing the causes of climate change by reducing concentrations of greenhouse gases in the atmosphere – mitigation and preparing for the consequences – adaptation. Strong national and international actions are required to reduce greenhouse gas emissions and building resilient communities; particularly, the legislative, executive and judicial branches all have a role to play. Understandably, it is a challenge for Myanmar to achieve climate change adaptation unless all the authorities and government sectors collectively consider each activity related to climate change.

Ethnicity is one of the primary lenses through which many scholars view conflict in Burma/Myanmar. It is important to understand the 'Wages of Burman-ness' and Burman privilege in contemporary Myanmar, whereby Burman-ness can be conceptualised as a form of institutionalised dominance, similar to Whiteness in many Western cultures (Walton, 2013). On the other hand, the internal conflict in Myanmar has primarily been ethnic-based since independence in 1948; an array of ethnic political movements and their armed wings have sought political, economic, cultural, and social rights as protection against domination by (majority) Burman authorities. Eventually, some kind of revolution must come without returning to the past (military era). For which, the movement of democracy alone is not enough. There needs to be a more progressive agenda for change, across ethnic lines, towards a fairer as well as freer society for all of Myanmar's peoples (Myint-U, 2021b). In this respect, understanding the culture of different Myanmar ethnicity is essential to develop different housing program for the diverse cultural and local context.

In the other study by the author, an enquiry was developed into the way homes in Myanmar manifest their culture and local contexts and traced changes from the archetypal safeguarding of occupants to more sophisticated modern-day concerns relating to resilience and safety, particularly about the way climate change and socio-political scenarios impacted in the making of homes (Zune et al., 2020a). The argument was developed using two methods: maps and narrative method and travel story narrative method.

For the map and narrative method, an observational analysis of eight Myanmar vernacular houses was a starting point, which are replicas of significant symbolic structures characteristic of the major ethnicities residing in the country. That vernacular study was partly presented in this thesis Chapter 1. The "maps and narrative" method was used to tell different stories about different house types in Myanmar within their climate, culture, and location settings and their influence on passive vernacular design for comfort and room configurations. They discoursed on how the human settlement historically developed and outlined the ways in which communities have made their homes, in terms of establishing vernacular practices, arranging room configurations and reflecting the given and changing climate and cultural contexts. The "maps and narrative" method (Ryan et al., 2016) supports the discussion of different stories associated with a map in different times and also allows the author to push forward the changing context in the making of homes in different locations.

Secondly, the author drew learnings from a "travel story narrative" exercise that followed video documentaries covering homes of the 21st century and beyond, referring to two videos originally aired as "*Anthony Bourdain: Parts Unknown*" by CNN (Bourdain, 2013) and "*Burma with Simon Reeve*" by BBC (Reeve, 2018). Bourdain is a world-renowned chef, bestselling author, and multiple Emmy-winning television personalities; his programme is epitomised by the opening referring to Myanmar: "*After 50 years of nightmare, something unexpected is happening here, and it's pretty incredible*". Reeve is a British author and television presenter, and his documentary explored the country's both rich culture and controversial experiences. Five years after Bourdain's visit to Myanmar, Reeve found that Myanmar is "*still a place of tragedy*". Documentary film has long been associated with travel and culture, and it can also provide the stories that make film-induced tourism so compelling while simultaneously providing a more human look at the area (Mecham, 2015).

The juxtaposition of these two narratives led the author to the suggestion that over the course of time, some things remain eternal in the making of homes, which are as true in Myanmar today as in vernacular homes of centuries ago, yet something must change to make homes, neighbourhoods, and cities safe and resilient to the global threats of climate change – just as vernacular architecture achieved such safety for local threats – keeping within the requirements and traditions of Myanmar people. The author argued that everything has changed in Myanmar homes' design, delivery and occupation, yet something must change in the near future in order to ensure homes are fit for purpose and climate change adaptation.

Considering the political crisis in Myanmar in 2021, every research-related action for Myanmar sustainable development plan and resilient housing has to accommodate a better understanding of the country's unstable economy and policy, inequity among ethnic groups, economic inequality, and the country's unique political economy as it has emerged since 1988, across a landscape dominated by both state and non-state armed groups. All those considerations would more or less affect the future research discussed in this thesis and the development of the country. It also means a qualitative change in what people do and the institutions in which they work. In this way, development entails a remaking of society (Myint-U, 2020). To realise the *Myanmar Sustainable Development Plan* (MSDP, 2018), Myanmar needs to reimagine its economic future with a new kind of democracy (Myint-U, 2021a). A reasonable housing policy may be developed with a dictatorship; however, climate change has already led to the migration of millions in Myanmar; the cyclone Nargis in 2008 was a piece of unchangeable evidence. A desperately poor and unequal country at war with itself will not produce anything other than a facade of democracy.

After two months of the military coup, at the time of submitting this thesis, no one could have imagined where Myanmar would still be in 2021. Nevertheless, climate change impacts are already affecting ecological and socio-economic systems, and it is anticipated that these impacts will continue well into the future. A solid basis for adaptation planning, implementation, monitoring and evaluation, targeting present and future climate change risks pertaining to Myanmar housing for different climate zones and different ethnic groups, will be possible if the people of Myanmar craft together a progressive agenda across ethnic lines, centred on equality and development as well as peace and justice.

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